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(54) Title: VIRTUAL REALITY IMMERSION SYSTEM

(57) Abstract: A virtual reality immersion system provides a head mounted display that contains a video camera and a video display. A plurality of target markers are distributed within a virtual environment room where each target is distinct from all other targets in the virtual environment room and distinct from rotated versions of itself. An automatic calibration program selects pair of targets from an image from the video camera. The selected pairs of targets are identified and the position of each target is calculated relative to the camera and relative to each other. The positions of each target pair are added to a list of relative target transforms. Video signals are processed to calculate the position of targets detected in each frame image using the relative target transforms and the effects of viewing angles are detected and a higher weight is given to targets that are detected at more reliable angles. The invention dynamically streams 3D content to the user through the video display. Once the target positions have been calculated, the invention determines the user position within the environment and when the user changes his viewpoint, the information from the calculated user position is used to change the position and angle of the 3D content and the 3D content is repositioned and streamed to the video display.

Virtual Reality Immersion System

BACKGROUND OF THE INVENTION

TECHNICAL FIELD

The invention relates to virtual reality and simulations. More particularly, the invention relates to the immersion of an observer into a virtual reality environment.

DESCRIPTION OF THE PRIOR ART

Virtual Reality (VR) is an artificial environment constructed by a computer that permits the user to interact with that environment as if the user were actually immersed in the environment. VR devices permit the user to see three-dimensional (3D) depictions of an artificial environment and to move within that environment.

VR broadly includes Augmented Reality (AR) technology, which allows a person to see or otherwise sense a computer-generated virtual world integrated with the real world. The "real world" is the environment that an observer can see, feel, hear, taste, or smell using the observer's own senses. The "virtual world" is defined as a generated environment stored in a storage medium or calculated using a processor.

There are a number of situations in which it would be advantageous to superimpose computer-generated information on a scene being viewed by a human viewer. For example, a mechanic working on a complex piece of equipment would benefit by having the relevant portion of the maintenance manual displayed within her field of view while she is looking at the equipment. Display systems that provide this feature are often referred to as "Augmented Reality" systems. Typically, these systems utilize a head-mounted display that allows the user's view of the real world to be enhanced or added to by "projecting" into it computer generated annotations or objects.

In several markets, there is an untapped need for the ability to insert human participants or highly realistic static or moving objects into a real world or virtual world environment in real-time. These markets include military training, computer games, and many other applications of VR, including AR. There are many systems in existence for producing texture-mapped 3D models of objects, particularly for e-commerce applications. They include methods using hand-built or CAD models, and a variety of methods that use 3D sensing technology. The current state-of-the-art systems for inserting objects have many disadvantages, including:

(a) Slow data acquisition time (models are built by hand or use slow automated systems);
(b) Inability to handle motion effectively (most systems only handle still or limited motion);
(c) Lack of realism (most systems have a "plastic" look or limits on the level of detail); and
(d) Limited size of the object to be captured.

Systems currently in use to insert humans into virtual environments include motion capture systems used by video game companies and movie studios, and some advanced research being done by the US Army STRICOM. The current state-of-the-art systems for inserting humans have many other disadvantages, including:

(a) most require some sort of marker or special suit be worn;
(b) Most give a coarse representation of the human in the simulated environment; and
(c) Few systems actually work in real-time; the ones that do are necessarily limited.

None of the prior art systems is capable of inserting static and dynamic objects, and humans and other living beings into a virtual environment, which allows a user to see the object or human as they currently look, in real-time, and from any viewpoint.

The completely artificial worlds of VR systems that are currently available do not allow the sort of immersion and believability that occurs with AR/MR. VR systems are also unable to include real-world-derived human subjects in VR environments. VR is an intrinsically limited idea because it forces the user to step outside of the physical real world. AR/MR are much more utilitarian technologies that can make use of the real world as necessary.

Further, none of the current technologies of motion tracking (from companies such as Polhemus of Colchester, VT, Ascension Technology Corp. of Burlington, VT, and Intersense, Inc., of Burlington, MA) seamlessly capture any sort of model or image of the subject. These approaches capture only motion data that must then be cleaned of errors and attached to polygonal models. The cleaning may be nearly as time-intensive as creating the animation by hand. Technologies that capture shape and texture information (laser scanners, etc.) cannot do so at interactive frame rates.

It would be advantageous to provide a virtual reality immersion system that immerses a user into a virtual environment and reacts to the user's movements and displays relative 3D content to the user in real time. It would further be advantageous to provide a virtual reality immersion system that tracks a user's position in a virtual environment using a set of target markers distributed throughout a room.

SUMMARY OF THE INVENTION

The invention provides a virtual reality immersion system. The invention immerses a user into a virtual environment by reacting to the user's movements and displaying relative 3D content to the user in real time. In addition, the invention tracks a user's position in the virtual environment using a set of target markers distributed throughout the virtual environment room.

A preferred embodiment of the invention provides a head mounted display (HMD) that contains a video camera and a video display. A plurality of target markers are distributed within a virtual environment room. Each target is distinct from all other targets in the virtual environment room and distinct from rotated versions of itself. An automatic calibration program selects pair of targets from an image from the video camera. The selected pairs of targets are identified and the position of each target is calculated relative to the camera. The position of each target in a pair is then calculated in relation to each other. The positions of each target pair are added to a list of relative target transforms.

During normal user mode, video signals are processed to calculate the position of targets detected in each frame image using the relative target transforms. The detection algorithm detects the effects of viewing angles and gives a higher weight to targets that are detected at more reliable angles. Once the target positions have been calculated, the invention determines the user position within the environment.

The invention dynamically streams 3D content to the user through the video display. When the user changes his viewpoint, the information from the calculated user position is used to change the position and angle of the 3D content. The 3D content is repositioned and streamed to the video display. The invention can also insert 3D video images of human beings, animals or other living beings or life forms, and any clothing or objects that they bring with them, into the virtual environment room.

Other aspects and advantages of the invention will become apparent from the following detailed description in combination with the accompanying drawings, illustrating, by way of example, the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic block diagram illustrating the system architecture of the Virtual Viewpoint system in accordance with one embodiment of the invention;

Fig. 2 is a flow diagram illustrating the components, functions and processes of the Virtual Viewpoint system in accordance with one embodiment of the invention;

Fig. 3 is a diagram illustrating the relative viewpoints of real cameras and virtual camera in the view generation process;

Fig. 4 is a diagram illustrating the relative viewpoints of real cameras and virtual camera to resolve an occlusion problem;

Fig. 5 is diagram illustrating the remote collaboration concept of the invention;

Fig. 6 is a diagram illustrating the user interface and the application of Virtual Viewpoint concept in video-conferencing in accordance with one embodiment of the invention;

Fig. 7 is a diagram illustrating marker detection and pose estimation;

Fig. 8 is a diagram illustrating virtual viewpoint generation by shape from silhouette;

Fig. 9 is a diagram illustrating the difference between the visual hull and the actual 3-D shape;

Fig. 10 is a diagram illustrating the system diagram of a videoconferencing system incorporating the Virtual Viewpoint concept of the invention;

Fig. 11 is a diagram illustrating a desktop 3-D augmented reality video-conferencing session;

Fig. 12 is a diagram illustrating several frames from a sequence in which the observer explores a virtual art gallery with a collaborator, which is generated by a system that incorporates the Virtual Viewpoint concept of the invention;

Fig. 13 is a diagram illustrating a tangible interaction sequence, demonstrating interaction between a user in augmented reality and collaborator in augmented reality, incorporating the Virtual Viewpoint concept of the invention;

Fig. 14 is a diagram illustrating the transformation of 2D video to 3D space according to the invention;

Fig. 15 is a diagram illustrating the use of a head mounted display to detect a 2D marker and display of 3D content at the marker position according to the invention;

Fig. 16 is a block schematic diagram of a system view of the invention according to the invention;

Fig. 17 is a flowchart showing overlaying of rendered virtual viewpoint content onto an original source video signal according to the invention;

Fig. 18 is a diagram of an exemplary set of target markers according to the invention;

Fig. 19 is a diagram illustrating an identification algorithm of set of target markers according to the invention;

Fig. 20 is a diagram illustrating an exemplary set of target markers distributed throughout a room according to the invention;

Fig. 21 is a flowchart of an automatic calibration process for creating a target transform list of target markers within a room according to the invention; and

Fig. 22 is a block schematic diagram of an task viewpoint of the invention according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

The invention is embodied in a virtual reality immersion system. A system according to the invention immerses a user into a virtual environment and reacts to the user's movements and displays relative 3D content to the user in real time. The invention additionally tracks a user's position in the virtual environment using a set of target markers distributed throughout the virtual environment room.

It is understood that the Virtual Viewpoint concept of the present invention may be applied for entertainment, sports, military training, business, computer games, education, research, etc. whether in an information exchange network environment (*e.g.*, videoconferencing) or otherwise.

Information Exchange Network

The detailed descriptions that follow are presented largely in terms of methods or processes, symbolic representations of operations, functionalities and features of the invention. These method descriptions and representations are the means used by those skilled in the art to most effectively convey the substance of their work to others skilled in the art. A software implemented method or process is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. These steps require physical manipulations of physical quantities. Often, but not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

Useful devices for performing the software implemented operations of the present invention include, but are not limited to, general or specific purpose digital processing and/or computing devices, which devices may be standalone devices or part of a larger system. The devices may be selectively activated or reconfigured by a program, routine and/or a sequence of instructions and/or logic stored in the devices. In short, use of the methods described and suggested herein is not limited to a particular processing configuration.

The Virtual Viewpoint platform in accordance with the present invention may involve, without limitation, standalone computing systems, distributed information exchange networks, such as public and private computer networks (*e.g.*, Internet, Intranet, WAN, LAN, etc.), value-added networks, communications networks (*e.g.*, wired or wireless networks), broadcast networks, and a homogeneous or heterogeneous combination of such networks. As will be appreciated by those skilled in the art, the networks include both hardware and software and can be viewed as either, or both, according to which description is most helpful for a particular purpose. For example, the network can be described as a set of hardware nodes that can be interconnected by a communications facility, or alternatively, as the communications facility, or alternatively, as the communications facility itself with or without the nodes. It will be further appreciated that the line between hardware and software is not always sharp, it being understood by those skilled in the art that such networks and communications facility involve both software and hardware aspects.

The Internet is an example of an information exchange network including a computer network in which the present invention may be implemented. Many servers are connected to many clients via Internet network, which comprises a large number of connected information networks that act as a coordinated whole. Various hardware and software components comprising the Internet network include servers, routers, gateways, etc., as they are well known in the art. Further, it is understood that access to the Internet by the servers and clients may be via suitable transmission medium, such as coaxial cable, telephone wire, wireless RF links, or the like. Communication between the servers and the clients takes place by means of an established protocol. As will be noted below, the Virtual Viewpoint system of the present invention may be configured in or as one of the servers, which may be accessed by users via clients.

Overall System Design

The Virtual Viewpoint System puts participants into real-time virtual reality distributed simulations without using body markers, identifiers or special apparel of any kind. Virtual Viewpoint puts the participant's whole body into the simulation, including their facial features, gestures, movement, clothing and any accessories. The Virtual Viewpoint system allows soldiers, co-workers or colleagues to train together, work together or collaborate face-to-face, regardless of each person's actual location.

Virtual Viewpoint is not a computer graphics animation but a live video recording of the full 3D shape, texture, color and sound of moving real-world objects. Virtual Viewpoint can create 3D interactive videos and content, allowing viewers to enter the scene and choose any viewpoint, as if the viewers are in the scene themselves. Every viewer is his or her own cameraperson with an infinite number of camera angles to choose from. Passive broadcast or video watchers become active scene participants.

Virtual Viewpoint Remote Collaboration consists of a series of simulation booths equipped with multiple cameras observing the participants' actions. The video from these cameras is captured and processed in real-time to produce information about the three-dimensional structure of each participant. From this 3D information, Virtual Viewpoint technology is able to synthesize an infinite number of views from any viewpoint in the space, in real-time and on inexpensive mass-market PC hardware. The geometric models can be exported into new simulation environments. Viewers can interact with this stream of data from any viewpoint, not just the views where the original cameras were placed.

System Architecture and Process

Fig. 1 illustrates the system architecture of the Virtual Viewpoint system based on 3D model generation and image-based rendering techniques to create video from virtual viewpoints. To capture the 3D video image of a subject (human or object), a number of cameras (*e.g.*, 2, 4, 8, 16 or more depending on image quality) are required. Reconstruction from the cameras at one end generates multiple video streams and a 3D model sequence involving 3D model extraction (*e.g.*, based on a "shape from silhouette" technique disclosed below). This information may be stored, and is used to generate novel viewpoints using video-based rendering techniques. The image capture and generation of the 3D model information may be done at a studio side, with the 3D image rendering done at the user side. The 3D model information may be transmitted from the studio to user via a gigabit Ethernet link.

Referring to Fig. 2, the Virtual Viewpoint system generally comprises the following components, process and functions:

(a) A number of cameras arranged around the human or object, looking inward. Practically, this can be as few as 4 cameras or so, with no upper limit other than those imposed by cost, space considerations, and necessary computing power. Image quality improves with additional cameras.

(b) A method for capturing the images digitally, and transferring these digital images to the working memory of a computer.

(c) A method for calibrating the cameras. The camera positions, orientations, and internal parameters such as lens focal length must be known relatively accurately. This establishes a mathematical mapping between 3D points in the world and where they will appear in the images from the cameras. Poor calibration will result in degraded image quality of the output virtual images.

(d) A method for determining the 3D structure of the human form or object in real-time. Any of a number of methods can be used. In order to control the cost of the systems, several methods have been developed which make use of the images from the cameras in order to determine 3D structure. Other options might include special-purpose range scanning devices, or a method called structured light. Embodiments of methods adopted by the present invention are described in more detail below.

(e) A method for encoding this 3D structure, along with the images, and translating it into a form that can be used in the virtual environment. This may include compression in order to handle the large amounts of data involved, and network protocols and interface work to insert the data into the system.

(f) Depending on the encoding chosen, software module may be necessary to compute the virtual views of the human or object for each entity in the system that needs to see such a viewpoint.

(g) Further processing may be required to incorporate the resulting virtual image of the human or object into the view of the rest of the virtual space.

3D Model Generation

In order for this system to work effectively, a method is needed for determining the 3D structure of a person or an arbitrary object. There are a variety of methods that can be used to accomplish this, including many that are available as commercial products. Generally, stereo vision techniques were found to be too slow and lacked the robustness necessary to make a commercial product.

In order to solve these two problems, a technique called "shape from silhouette" or, alternatively, "visual hull construction" was developed . There are at least three different methods of extracting shapes from silhouettes:

(a) Using the silhouettes themselves as a 3D model: This technique is described hereinbelow, which is an improvement over the concept developed at the MIT Graphics Laboratory (MIT Graphics Lab website: http://graphics.lcs.mit.edu/~wojciech/vh/).

(b) Using voxels to model the shape: This technique has been fully implemented, and reported by Zaxel Systems, Inc., the assignee of the present invention, in the report entitled Voxel-Based Immersive Environments (31-May-2000); (Final Report to Project Sponsored by Defense Advanced Research Projects Agency (DOD) (ISO) ARPA Order D611/70; Issued by U.S. Army Aviation and Missile Command Under Contract No. DAAH01-00-C-R058 – unclassified, approved for public release/unlimited distribution. The inventive concepts disclosed therein have been described in U.S. Patent Ser. No. 6,573,912 and U.S. Patent Application No. 10/388,836, filed 14 March 2003, both owned by the Applicant.) The relatively large storage requirements under this technique could be partially alleviated by using an octree-based model.

(c) Generating polygonal models directly from silhouettes. This is a rather complicated technique, but it has several advantages, including being well suited for taking advantage of modern graphics hardware. It also is the easiest system to integrate into the simulated environment. Reference is made to a similar technique developed at the University of Karlsruhe (Germany) (http://i31www.ira.uka.de/diplomarbeiten/da_martin_loehlein/Reconstruction.html)

Camera Calibration

3D reconstruction and rendering require a mapping between each image and a common 3D coordinate system. The process of estimating this mapping is called camera calibration. Each camera in a multi-camera system must be calibrated, requiring a multi-camera calibration process. The mapping between one camera and the 3D world can be approximated by an 11-parameter camera model, with parameters for camera position (3) and orientation (3), focal length (1), aspect ratio (1), image center (2), and lens distortion (1). Camera calibration estimates these 11 parameters for each camera.

The estimation process itself applies a non-linear minimization technique to the samples of the image-3D mapping. To acquire these samples, an object must be precisely placed in a set of known 3D positions, and then the position of the object in each image must be computed. This process requires a calibration object, a way to precisely position the object in the scene, and a method to find the object in each image. For a calibration object, a calibration plane approximately 2.5 meters and by 2.5 meters is designed and built, which can be precisely elevated to 5 different heights. The plane itself has 64 LEDs laid out in an 8x8 grid, 30cm between each LED. The LEDs are activated one at a time so that any video image of the plane will have a single bright spot in the image. By capturing 64 images from each camera, each LED is imaged once by each camera. By sequencing the LEDs in a known order, software can determine the precise3D position of the LED. Finally, by elevating the plane to different heights, a set of points in 3 dimensions can be acquired. Once all the images are captured, a custom software system extracts the positions of the LEDs in all the images and then applies the calibration algorithm. The operator can see the accuracy of the camera model, and can compare across cameras. The operator can also remove any

LEDs that are not properly detected by the automated system. (The actual mathematical process of using the paired 3D points and 2D image pixels to determine the 11 parameter model is described in: Roger Y. Tsai; "A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses"; IEEE Journal of Robotics and Automation RA-3(4): 323-344, August 1987.

Another camera calibration scheme is discussed below in connection with the embodiment in which the novel Virtual Viewpoint concept is applied to videoconferencing.

Image-based Rendering Using Silhouettes as an Implicit 3D Model

The goal of the algorithm described here is to produce images from arbitrary viewpoints given images from a small number (5-20 or so) of fixed cameras. Doing this in real time will allow for a 3D TV experience, where the viewer can choose the angle from which they view the action.

The technique described here is based on the concept of Image-Based Rendering (IBR) [see for example, E. Chen and L. Williams. View Interpolation for Image Synthesis. SIGGRAPH'93, pp. 279-288, 1993; S. Laveau and O. D. Faugeras. "3-D Scene Representation as a Collection of Images," In *Proc. of 12th IAPR Intl. Conf. on Pattem Recognition*, volume 1, pages 689–691, Jerusalem, Israel, October 1994; M. Levoy and P. Hanrahan. Light Field Rendering. SIGGRAPH '96, August 1996; W.R. Mark. "Post-Rendering 3D Image Warping: Visibility, Reconstruction, and Performance for Depth-Image Warping," Ph.D. Dissertation, University of North Carolina, April 21, 1999. (Also UNC Computer Science Technical Report TR99-022); L. McMillan. "An Image-Based Approach to Three-Dimensional Computer Graphics," Ph.D. Dissertation, University of North Carolina, April 1997. (Also UNC Computer Science Technical Report TR97-013)]. Over the last few years research into IBR has produced several mature systems [see for example, W.R. Mark. "Post-Rendering 3D Image Warping: Visibility, Reconstruction, and Performance for Depth-Image Warping," Ph.D. Dissertation, University of North Carolina, April 21, 1999. (Also UNC Computer Science Technical Report TR99-022); L. McMillan. "An Image-Based Approach to Three-Dimensional Computer Graphics," Ph.D. Dissertation, University of North Carolina, April 1997. (Also UNC Computer Science Technical Report TR97-013)]. The concept behind IBR is that given a 3D model of the geometry of the scene being viewed, and several images of that scene, it is possible to predict what the scene would look like from another viewpoint. Most IBR research to date has dealt with range maps as the basic 3D model data. A range map provides distance at each pixel to the 3D object being observed.

Shape from Silhouette (a.k.a. voxel intersection) methods have long been known to provide reasonably accurate 3D models from images with a minimum amount of computation [see for example, T.H. Hong and M. Schneier, "Describing a Robot's Workspace Using a Sequence of Views from a Moving Camera," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 7, pp. 721-726, 1985]. The idea behind shape from silhouette is to start with the assumption that the entire world is occupied. Each camera placed in the environment has a model of what the background looks like. If a pixel in a given image looks like the background, it is safe to assume that there are no objects in the scene between the camera and the background along the ray for that pixel. In this way the "silhouette" of the object (its 2D shape as seen in front of a known background) is used to supply 3D shape information. Given multiple views and many pixels, one can "carve" away the space represented by the background pixels around the object, leaving a reasonable model of the foreground object, much as a sculptor must carve away stone.

Shape from Silhouette is usually used to generate a voxel model, which is a 3D data structure where space is divided into a 3D grid, and each location in space has a corresponding memory location. The memory locations contain a value indicating whether the corresponding location in space is occupied or empty. Some researchers have used Shape from Silhouette to generate a voxel model, from which they produce a range map that they can use as a basis for IBR. The methods for producing a range map from a voxel model are complex, time-consuming, and inaccurate. The inaccuracy results from the fact that the grid has finite resolution and is aligned with a particular set of coordinate axes. The approach described here is a direct method for computing depth and pixel values for IBR using only the silhouette masks, without generating an intermediate voxel model. This has several advantages, but the most compelling advantage is that the results are more accurate, since the voxel model is only an approximation to the information contained in the silhouettes. Other related approaches include Space Carving, and Voxel Coloring.

Algorithm Concept

3D reconstruction using the voxel intersection method slices away discrete pieces of 3D space that are considered to be unoccupied. When a particular camera sees a background pixel, it is safe to assume that the space between the camera and the background is empty. This space is actually shaped like a rectangular pyramid with its tip at the focus of the camera, extending out until it intersects the background.

The key idea here is that if a particular 3D location in space is seen as unoccupied by any one camera, the point will be considered unoccupied regardless of what the other cameras see at that location.

For each pixel in the virtual image, a test point is moved out along the ray corresponding to that pixel, as illustrated in Fig. 3. At each point along the ray, the corresponding pixel in each image is evaluated to see whether the pixel sees the background. In the example of Fig. 3, the example ray is followed outward from the point marked A (the virtual viewpoint or virtual camera V. If any of the cameras sees background at a particular point, that point is considered to be unoccupied, so the next step is to move one step farther out along the ray; this process is repeated. In the example, for each of the points from A to B, no camera considers the points to be occupied. From B to C, the camera C1 on the right sees the object X, but the camera C2 on the left sees nothing. From C to D, again no camera sees anything. From D to E, the camera C2 on the left sees the object Z, but the camera C1 on the right sees nothing. From E to F again neither camera sees anything. Finally, at F, both cameras agree that the point is occupied by the object Y and the search stops.

When a 3D point that all cameras agree is occupied is found, depth of that pixel is found, as well as knowing the position of the point in all of the images. In order to render the pixel, the pixels from the real images are combined.

Algorithm Description

This section contains a high-level description of the algorithm in pseudocode. The subsequent section contains a more detailed version that would be useful to anyone trying to implement the algorithm. This algorithm requires enough information about camera geometry that, given a point in the virtual camera and a distance, where the corresponding point would appear in each of the real cameras can be computed. The only other information needed is the set of silhouette masks from each camera.

```
for each pixel (x,y) in the virtual camera
    distance = 0
    searched_cams = {}
    while searched_cams != all_cams, choose cam from all_cams - searched_cams
```

```
        Project the ray for (x,y) in the virtual camera into the image for cam
        Let (cx,cy) be the point that is distance along the ray

        (ox,oy) = (cx,cy)
        while point at (ox,oy) in mask from cam is OCCUPIED
          Use line rasterization algorithm to move (ox,oy) outward by one pixel
        end

        if (ox,oy) = (cx,cy)
          searched_cams = searched_cams + {cam}
        else
          Use (ox,oy) to compute new distance
          searched_cams = {}
        end
    end
    distance is the depth of the point (x,y)
end
```

The usual line rasterization algorithm was developed by Bresenham in 1965, though any algorithm will work. Bresenham's algorithm is discussed in detail Foley's article [see Foley, van Dam, Feiner, and Hughes, "Computer Graphics Principles and Practice," Second Edition, Addison Wesley, 1990].

- Algorithm as Implemented: Depth from Silhouette Mask Images

This description of the algorithm assumes a familiarity with some concepts of computer vision and computer graphics, namely the pinhole camera model and the matrix representation of it using homogeneous coordinates. A good introductory reference to the math can be found in Chapters 5 and 6 of Foley's article [see Foley, van Dam, Feiner, and Hughes, "Computer Graphics Principles and Practice," Second Edition, Addison Wesley, 1990].

<u>Inputs:</u>

1. Must have known camera calibration in the form of 4x4 projection matrices $\mathbf{A}_{cam}$ for each camera. This matrix takes the 3D homogeneous coordinate in space and converts it into an image-centered coordinate. The projection onto the image plane is accomplished by dividing the x and y coordinates by the z coordinate.
2. The virtual camera projection matrix $\mathbf{A}_{virt}$

3. The mask images

Outputs:

1. A depth value at each pixel in the virtual camera. This depth value represents the distance from the virtual camera's projection center to the nearest object point along the ray for that pixel.

Algorithm Pseudocode:

```
For each camera cam, $T_{cam}=A_{cam}A_{virt}^{-1}$
For each pixel (x,y) in the virtual camera
distance = 0
searched_cams = {}
While searched_cams != all_cams, choose cam from all_cams -  searched_cams
      epipole = ($T_{cam}(1,4)$,$T_{cam}(2,4)$,$T_{cam}(3,4)$)
      infinity_point = ($T_{cam}(1,1)$ * x + $T_{cam}(1,2)$ * y + $T_{cam}(1,3)$,
                        $T_{cam}(2,1)$ * x + $T_{cam}(2,2)$ * y + $T_{cam}(2,3)$,
                        $T_{cam}(3,1)$ * x + $T_{cam}(3,2)$ * y + $T_{cam}(3,3)$)

      close_point = epipole + distance * infinity_point
      far_point = infinity_point

      cx = close_point(1)/close_point(3)
      cy = close_point(2)/close_point(3)
      fx = far_point(1)/far_point(3)
      fy = far_point(2)/far_point(3)

      (clip_cx, clip_cy, clip_fx, clip_fy) = clip_to_image(cx,cy,fx,fy)
      (ox,oy) = search_line(mask(cam),clip_cx,clip_cy,clip_fx,clip_fy)
      if (ox,oy) = (clip_cx,clip_cy)
            searched_cams = searched_cams + {cam}
      else
            distance = compute_distance($T_{cam}$,ox,oy)
            searched_cams = {}
      end
   end
   depth(x,y) = distance
end
```

Explanation:

(a) Every pixel in the virtual image corresponds to a ray in space. This ray in space can be seen as a line in each of the real cameras. This line is often referred to as the epipolar line. In homogeneous coordinates, the endpoints of this line are the two variables **epipole** and **infinity_point**. Any point between these two points can be found by taking a linear combination of the two homogeneous coordinates.

(b) At any time during the loop, the points along the ray from 0 to **distance** have been found to be unoccupied. If all cameras agree that the point at distance is occupied, the loop exits and that distance is considered to be the distance at **(x,y)**.

(c) clip_to_image() makes sure that the search line is contained entirely within the image by "clipping" the line from **(cx,cy)** to **(fx,fy)** so that the endpoints lie within the image coordinates.

(d) search_line() walks along the line in mask until a pixel that is marked occupied in the mask is found. It returns this pixel in **(ox,oy)**.

(e) compute_distance() simply inverts the equation used to get **close_point** in order to compute what the distance should be for a given **(ox,oy)**.

(f) As a side effect, the final points **(ox,oy)** in each camera are actually the pixels that are needed to combine to render the pixel **(x,y)** in the virtual camera. The following sections will discuss methods for doing this combination.

The Occlusion Problem

Once there is a set of pixels to render in the virtual camera, they are used to select a color for each virtual camera pixel. One of the biggest possible problems is that most of the cameras are not looking at the point to be rendered. For many of the cameras, this is obvious: they are facing in the wrong direction and seeing the backside of the object. But this problem can occur even when cameras are pointing in almost the same direction as the virtual camera, because of occlusion. In this context, occlusion refers to the situation where another object blocks the view of the object that must be rendered. In this case, it is desirable not to use the pixel for the other object when the virtual camera should actually see the object that is behind it.

In order to detect occlusions, the following technique is applied, as shown in Fig. 4. For each camera that is facing in the same direction as the virtual camera V, a depth map is pre-computed using the algorithm described in the previous section. To determine if a pixel from a given camera (C1 and C2) is occluded in the virtual view or not, the computed depth is used in the virtual camera V to transform the virtual pixel into the real camera view. If the depth of the pixel from the virtual view (HF) matches the depth computed for the real view (HG), then the pixel is not occluded and the real camera can be used for rendering. Otherwise pixels from a different camera must be chosen. In other words, if the difference between the depth from the virtual camera (HF) and that from the real camera (HG) is bigger than a threshold, then that real camera cannot be used to render the virtual pixel.

Deriving Information About Object Shape

After computing the 3D position of a particular virtual pixel and determining which cameras can see it based on occlusion, in general there may still be a number of cameras to choose from. These cameras are likely to be observing the surface of the object at a variety of angles. If a camera that sees the surface at a grazing angle is chosen, one pixel from the camera can cover a large patch of the object surface. On the other hand if a camera that sees the surface at close to the surface normal direction is used, each pixel will cover a relatively smaller portion of the object surface. Since the latter case provides for the maximum amount of information about surface detail, it is the preferred alternative.

The last camera that causes a point to move outward along the ray for a given pixel (this is the last camera which causes the variable distance to change in the algorithm) can provide some information about this situation. Since this camera is the one that carves away the last piece of volume from the surface for this pixel, it provides information about the local surface orientation. The best camera direction (the one that is most normal to the surface) should be perpendicular to the direction of the pixel in the mask that defines the surface for the last camera. This provides one constraint on the optimal viewing direction, leaving a two dimensional space of possible optimal camera directions. In order to find another constraint, it is necessary to look at the shape of the mask near the point where the transition from unoccupied to occupied occurred. It is desirable to find a camera that is viewing the edge of the surface that can be seen in the mask in a normal direction. This direction can be computed from the mask. Given this edge direction, it can be decided which cameras are observing the surface from directions that are close to the optimal direction.

More Accurate Object Shape Using Color Constraints

The Shape from Silhouette method has known limitations in that there are shapes that it cannot model accurately, even with an infinite number of cameras [see for example, A Laurentini. How Far 3D Shapes Can Be Understood from 2D Silhouettes. IEEE

Transactions on Pattern Analysis and Machine Intelligence, 17(2):188-195, 1995]. This problem is further exacerbated when a small number of cameras are used. For example, the shapes derived from the silhouettes tend to contain straight edges, even when the actual surface is curved.

In order to more accurately model the surface, it is possible to add a color consistency constraint to the algorithm discussed here. The basic idea is that if one has the correct 3D information about the surface being viewed for a particular pixel, then all of the cameras that can see that point should agree on its color. If the cameras report wildly different colors for the point, then something is wrong with the model. After accounting for occlusion and grazing-angle effects, the most likely explanation is that the computed distance to the surface is incorrect. Since the algorithm always chooses the smallest distance to the surface that is consistent with all of the silhouettes, it tends to expand objects outward, toward the camera.

After finding the correct distance to the object using the silhouette method for a given pixel, the example ray is followed outward along the ray for that pixel until the cameras that are able to see the points all agree on a color. The color that they agree upon should be the correct color for the virtual pixel.

To determine the color for virtual pixels, the real cameras closest to the virtual camera are identified, after which each of the cameras is tested for occlusion. Pixels from cameras that pass the occlusion test are averaged together to determine the pixel color.

Advantages

Advantages of the silhouette approach herein include:

1. The silhouettes have about the same size as the voxel model, so similar transmission costs.
2. The depth information can be derived in a computationally efficient manner on the client end.
3. The resulting model is more accurate than a voxel model.
4. Avoids unneeded computation, since only the relevant parts of the 3D model are constructed as they are used.
5. Depth map and rendered image are computed simultaneously.
6. A depth map from the perspective of the virtual camera is generated; this can be used for depth cueing (*e.g.* inserting simulated objects into the environment).
7. Detection and compensation for object occlusion is handled easily.

Remote Collaboration

The Virtual Viewpoint™ System puts participants into real-time virtual reality distributed simulations without using body markers, identifiers or special apparel of any kind. Virtual Viewpoint puts the participant's whole body into the simulation, including their facial features, gestures, movement, clothing and any accessories. The Virtual Viewpoint System allows soldiers, co-workers or colleagues to train together, work together or collaborate face-to-face, regardless of each person's actual location. For example, Fig. 5 illustrates the system merging the 3D video image renditions of two soldiers, each originally created by a set of 4 video cameras arranged around the scene.

As an example, using the Virtual Viewpoint technology, a participant in Chicago and a participant in Los Angeles each step off the street and into their own simulation booth, and both are instantly in the same virtual room where they can collaboratively work or train. They can talk to one another, see each other's actual clothing and actions, all in real-time. They can walk around one another, move about in the virtual room and view each other from any angle. Participants enter and experience simulations from any viewpoint and are immersed in the simulation.

Numerous other objects, including real-time, Virtual Viewpoint offline content, even objects from other virtual environments, can be inserted into the scene. The two soldiers can be inserted into an entirely new virtual environment and interact with that environment and each other. This is the most realistic distributed simulation available.

Below is a specific embodiment of the application of the inventive Virtual Viewpoint concept to real-time 3D interaction for augmented and virtual Reality. By way of example and not limitation, the embodiment is described in reference to videoconferencing. This example further illustrates the concepts described above.

Videoconferencing with Virtual Viewpoint

Introduction

A real-time 3-D augmented reality (AR) video-conferencing system is described below in which computer graphics creates what may be the first real-time "holo-phone". . With this technology, the observer sees the real world from his viewpoint, but modified so that the image of a remote collaborator is rendered into the scene. The image of the collaborator is registered with the real world by estimating the 3-D transformation between the camera and a fiducial marker. A novel shape-from-silhouette algorithm, which generates the appropriate view of the collaborator and the associated depth map in real time, is described. This is based on simultaneous measurements from fifteen calibrated cameras that surround the collaborator. The novel view is then superimposed upon the real world and appropriate directional audio is added. The result gives the strong impression that the virtual collaborator is a real part of the scene. The first demonstration of interaction in virtual environments with a "live" fully 3-D collaborator is presented. Finally, interaction between users in the real world and collaborators in a virtual space, using a "tangible" AR interface, is considered.

Existing conferencing technologies have a number of limitations. *Audio-only conferencing* removes visual cues vital for conversational turn-taking. This leads to increased interruptions and overlap [E. Boyle, A. Anderson and A. Newlands. The effects of visibility on dialogue and performance in a co-operative problem solving task. Language and Speech, 37(1): 1-20, January-March 1994], and difficulty in disambiguating between speakers and in determining willingness to interact [D. Hindus, M. Ackerman, S. Mainwaring and B.Starr. Thunderwire: A field study of an audio-only media space. In Proceedings of CSCW, November 1996]. *Conventional 2-D video-conferencing* improves matters, but large user movements and gestures cannot be captured [C. Heath and P. Luff. Disembodied Conduct: Communication through video in a multimedia environment. In Proceedings of CHI 91, pages 93-103, ACM Press, 1991], there are no spatial cues between participants [A. Sellen. and B. Buxton. Using Spatial Cues to Improve Videoconferencing. In Proceedings CHI '92, pages 651-652, ACM: May 1992] and participants cannot easily make eye contact [A. Sellen, Remote Conversations: The effects of mediating talk with technology. Human Computer Interaction, 10(4): 401-444, 1995]. Participants can only be viewed in front of a screen and the number of participants is limited by monitor resolution. These limitations disrupt fidelity of communication [S. Whittaker and B. O'Connaill, The Role of Vision in Face-to-Face and Mediated Communication. In Finn, K., Sellen, A., Wilbur, editors, Video-Mediated Communication, pages 23-49. S. Lawerance Erlbaum Associates, New Jersey, 1997] and turn taking [B. O'Conaill, S. Whittaker, and S. Wilbur, Conversations over video conferences: An evaluation of the spoken aspects of video-mediated communication. Human-Computer Interaction, 8: 389-428, 1993], and increase interruptions and overlap [B. O'Conaill, and S. Whittaker, Characterizing, predicting and measuring video-mediated communication: a conversational approach. In K. Finn, A. Sellen, S. Wilbur (Eds.), Video mediated communication. LEA: NJ, 1997]. *Collaborative virtual environments* restore spatial cues common in face-to-face conversation [S. Benford, and L. Fahlen, A Spatial Model of Interaction in Virtual Environments. In Proceedings of Third European Conference on Computer Supported

Cooperative Work (ECSCW'93), Milano, Italy, September 1993], but separate the user from the real world. Moreover, non-verbal communication is hard to convey using conventional avatars, resulting in reduced presence [A. Singer, D. Hindus, L. Stifelman and S. White, Tangible Progress: Less is more in somewire audio spaces. In Proceedings of CHI 99, pages 104-111, May 1999].

Perhaps closest to the goal of perfect tele-presence is the Office of the Future work [R. Raskar, G. Welch, M. Cutts, A. Lake, L. Stesin and H. Fuchs, The Office of the Future: A unified approach to image based modeling and spatially immersive displays. SIGGRAPH 98 Conference Proceedings, Annual Conference Series, pages 179-188, ACM SIGGRAPH, 1998], and the Virtual Video Avatar of Ogi et al. [T. Ogi,, T. Yamada, K. Tamagawa, M. Kano and M. Hirose, Immersive Telecommunication Using Stereo Video Avatar. IEEE VR 2001, pages 45-51, IEEE Press, March 2001]. Both use multiple cameras to construct a geometric model of the participant, and then use this model to generate the appropriate view for remote collaborators. Although impressive, these systems only generate a 2.5-D model – one cannot move all the way around the virtual avatar and occlusion problems may prevent transmission. Moreover, since the output of these systems is presented via a stereoscopic projection screen and CAVE respectively, the display is not portable.

The Virtual Viewpoint technology resolves these problems by developing a 3-D mixed reality video-conferencing system. (See Fig. 6, illustrating how observers view the world via a head-mounted display (HMD) with a front mounted camera. The present system detects markers in the scene and superimposes live video content rendered from the appropriate viewpoint in real time). The enabling technology is a novel algorithm for generating arbitrary novel views of a collaborator at frame rate speeds. These methods are also applied to communication in virtual spaces. The image of the collaborator from the viewpoint of the user is rendered, permitting very natural interaction. Finally, novel ways for users in real space to interact with virtual collaborators are developed, using a tangible user interface metaphor.

System Overview

Augmented reality refers to the real-time insertion of computer-generated three-dimensional content into a real scene (see R.T. Azuma. "A survey of augmented reality." Presence, 6(4): 355-385, August 1997, and R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier and B. MacIntyre. Recent Advances in Augmented Reality. IEEE Computer Graphics and Applications, 21(6): 34-37, November/December 2001for reviews). Typically, the observer views the world through an HMD with a camera attached to the front. The video is captured, modified and relayed to the observer in real time. Early studies, such as S. Feiner, B. MacIntyre, M. Haupt and E. Solomon. Windows on the World: 2D Windows for 3D Augmented Reality. In Proceedings of UIST 93, pages 145-155, Atlanta, Ga, 3-5 November, 1993, superimposed two-dimensional textual information onto real world objects. However, it has now become common to insert three-dimensional objects.

In the present embodiment, live image of a remote collaborator is inserted into the visual scene. (See Fig. 6). As the observer moves his head, this view of the collaborator changes appropriately. This results in the stable percept that the collaborator is three dimensional and present in the space with the observer.

In order to achieve this goal, the following is required for each frame:

(a) The pose of the head-mounted camera relative to the scene is estimated.

(b) The appropriate view of the collaborator is generated.

(c) This view is rendered into the scene, possibly taking account of occlusions.

Each of these problems is considered in turn.

Camera Pose Estimation

The scene was viewed through a Daeyang Cy-Visor DH-4400VP head mounted display (HMD), which presented the same 640x480 pixel image to both eyes. A PremaCam SCM series color security camera was attached to the front of this HMD. This captures 25 images per second at a resolution of 640x480.

The marker tracking method of Kato is employed [H. Kato and M. Billinghurst, Marker tracking and HMD calibration for a video based augmented reality conferencing system, Proc. IWAR 1999, pages 85-94, 1999]. The pose estimation problem is simplified by inserting 2-D square black and white fiducial markers into the scene. Virtual content is associated with each marker. Since both the shape and pattern of these markers is known, it is easy to both locate these markers and calculate their position relative to the camera.

In brief, the camera image is thresholded and contiguous dark areas are identified using a connected components algorithm. A contour seeking technique identifies the outline of these regions. Contours that do not contain exactly four corners are discarded. The corner positions are estimated by fitting straight lines to each edge and determining the points of intersection. A projective transformation is used to map the enclosed region to a standard shape. This is then cross-correlated with stored patterns to establish the identity and orientation of the marker in the image (see Fig. 7, illustrating marker detection and pose estimation; the image is thresholded and connected components are identified; edge pixels are located and corner positions, which determine the orientation of the virtual content, are accurately measured; and region size, number of corners, and template similarity are used to reject other dark areas in the scene). For a calibrated camera, the image positions of the marker corners uniquely identify the three-dimensional position and orientation of the marker in the world. This information is expressed as a Euclidean transformation matrix relating the camera and marker co-ordinate systems, and is used to render the appropriate view of the virtual content into the scene.

It is imperative to obtain precise estimates of the camera parameters. First, the projective camera parameters must be simulated in order to realistically render three-dimensional objects into the scene. Second, any radial distortion must be compensated for when captured video is displayed to the user.

In the absence of radial distortion, straight lines in the world generate straight lines in the image. Hence, straight lines were fitted to the image of a regular 2D grid of points. The distortion parameter space is searched exhaustively to maximize goodness of fit. The center point of the distortion and the second order distortion co-efficient is estimated in this way. The camera perspective projection parameters (focal length and principal point) are estimated using a regular 2-D grid of dots. Given the exact position of each point relative to the grid origin, and the corresponding image position, one can solve for the camera parameters using linear algebra. Software for augmented reality marker tracking and calibration can be downloaded from “http://www.hitl.washington.edu/artoolkit/”.

Model Construction

In order to integrate the virtual collaborator seamlessly into the real world, the appropriate view for each video frame must be generated. One approach is to develop a complete 3D depth reconstruction of the collaborator, from which an arbitrary view can be generated. Depth information could be garnered using stereo-depth. Stereo reconstruction can been achieved at frame rate [T. Kanade, H. Kano, S. Kimura, A. Yoshida and O. Kazuo, “Development of a Video-Rate Stereo Machine.”

Proceedings of International Robotics and Systems Conference, pages 95-100, Pittsburgh, PA, August 1995], but only with the use of specialized hardware. However, the resulting dense depth map is not robust, and no existing system places cameras all round the subject.

A related approach is image-based rendering, which sidesteps depth-reconstruction by warping between several captured images of an object to generate the new view. Seitz and Dyer [S.M. Seitz and C.R. Dyer, View morphing, SIGGRAPH 96 Conference Proceedings, Annual Conference Series, pages 21-30. ACM SIGGRAPH 96, August 1996] presented the first image-morphing scheme that was guaranteed to generate physically correct views, although this was limited to novel views along the camera baseline. Avidan and Shashua [S. Avidan and A. Shashua. Novel View Synthesis by Cascading Trilinear Tensors. IEEE Transactions on Visualization and Computer Graphics, 4(4): 293-305, October-December 1998] presented a more general scheme that allowed arbitrary novel views to be generated from a stereoscopic image pair, based on the calculation of the tri-focal tensor. Although depth is not explicitly computed in these methods, they still require dense matches computation between multiple views and are hence afflicted with the same problems as depth from stereo.

A more attractive approach to fast 3D model construction is shape-from-silhouette. A number of cameras are placed around the subject. Each pixel in each camera is classified as either belonging to the subject (foreground) or the background. The resulting foreground mask is called a "silhouette". Each pixel in each camera collects light over a (very narrow) rectangular-based pyramid in 3D space, where the vertex of the pyramid is at the focal point of the camera and the pyramid extends infinitely away from this. For background pixels, this space can be assumed to be unoccupied. Shape-from-silhouette algorithms work by initially assuming that space is completely occupied, and using each background pixel from each camera to carve away pieces of the space to leave a representation of the foreground object.

Clearly, the reconstructed model will improve with the addition of more cameras. However, it can be proven that the resulting depth reconstruction may not capture all aspects of the true shape of the object, even given an infinite number of cameras. The reconstructed shape was termed the "visual hull" by Laurentini [A. Laurentini, The Visual Hull Concept for Sillhouette Based Image Understanding. IEEE PAMI, 16(2): 150-162, February 1994], who did the initial work in this area.

Despite these limitations, shape-from-silhouette has three significant advantages over competing technologies. First, it is more robust than stereovision. Even if background pixels are misclassified as part of the object in one image, other silhouettes are likely to carve away the offending misclassified space. Second, it is significantly faster than either stereo, which requires vast computation to calculate cross-correlation, or laser range scanners, which generally have a slow update rate. Third, the technology is inexpensive relative to methods requiring specialized hardware.

Application of Virtual Viewpoint System

For these reasons, the Virtual Viewpoint system in this embodiment is based on shape-from-silhouette information. This is the first system that is capable of capturing 3D models and textures at 30 fps and displaying them from an arbitrary viewpoint.

The described system is an improvement to the work of Matusik et al. [W. Matusik, C. Buehler, R. Raskar, S.J. Gortler and L. McMillan, Image-Based Visual Hulls, SIGGRAPH 00 Conference Proceedings, Annual Conference Series, pages 369-374, 2000] who also presented a view generation algorithm based on shape-from-silhouette. However, the algorithm of the present system is considerably faster. Matusik et al. can generate 320x240 pixel novel views at 15 fps with a 4 camera system, whereas the present system produces 450x340 images at 30 fps, based on 15 cameras. The principal reason for the performance improvement is that our algorithm requires only computation of an image-based depth map from the perspective of the virtual camera, instead of the generating the complete visual hull.

Virtual Viewpoint Algorithm

Given any standard 4x4 projection matrix representing the desired virtual camera, the center of each pixel of the virtual image is associated with a ray in space that starts at the camera center and extends outward. Any given distance along this ray corresponds to a point in 3D space. In order to determine what color to assign to a particular virtual pixel, the first (closest) potentially occupied point along this ray must be known. This 3D point can be projected back into each of the real cameras to obtain samples of the color at that location. These samples are then combined to produce the final virtual pixel color.

Thus the algorithm performs three operations at each virtual pixel:

(a) Determine the *depth* of the virtual pixel as seen by the virtual camera.

(b) Find corresponding pixels in nearby real images

(c) Determine pixel color based on all these measurements.

(a) Determining Pixel Depth

The depth of each virtual pixel is determined by an explicit search. The search starts at the virtual camera projection center and proceeds outward along the ray corresponding to the pixel center. (See Fig. 8, illustrating virtual viewpoint generation by shape from silhouette; points which project into the background in any camera are rejected; the points from A to C have already been processed and project to background in both images, so are marked as unoccupied (magenta); the points yet to be processed are marked in yellow; and point D is in the background in the silhouette from camera 2, so it will be marked as unoccupied and the search will proceed outward along the line.). Each candidate 3D point along this ray is evaluated for potential occupancy. A candidate point is unoccupied if its projection into any of the silhouettes is marked as background. When a point is found for which all of the silhouettes are marked as foreground, the point is considered potentially occupied, and the search stops.

It is assumed that the subject is completely visible in every image. To constrain the search for each virtual pixel, the corresponding ray is intersected with the boundaries of each image. The ray is projected into each real image to form the corresponding epipolar line. The points where these epipolar lines meet the image boundaries are found and these boundary points are projected back onto the ray. The intersections of these regions on the ray define a reduced search space. If the search reaches the furthest limit of this region without finding any potentially occupied pixels, the virtual pixel is marked as background.

The resulting depth is an estimate of the closest point along the ray that is on the surface of the visual hull. However, the visual hull may not accurately represent the shape of the object and hence this 3D point may actually lie outside of the object surface. (See Fig. 8).

(b) Determining Candidate Cameras

Since the recovered 3D positions of points are not exact, care needs to be taken in choosing the cameras from which pixel colors will be combined (See Fig. 9, illustrating the difference between the visual hull and the actual 3-D shape; the point on the visual hull does not correspond to a real surface point, so neither sample from the real cameras is appropriate for virtual camera pixel B; and, in this case, the closer real camera is preferred, since its point of intersection with the object is closer to the correct one.).

Depth errors will cause the incorrect pixels to be chosen from each of the real camera views. This invention aims to minimize the visual effect of these errors.

In general it is better to choose incorrect pixels that are physically closest to the simulated pixel. The optimal camera should be the one minimizing the angle between the rays corresponding to the real and virtual pixels. For a fixed depth error, this minimizes the distance between the chosen pixel and the correct pixel. The cameras proximity is ranked once per image, based on the angle between the real and virtual camera axes.

It can now be computed where the virtual pixel lies in each candidate camera's image. Unfortunately, the real camera does not necessarily see this point in space - another object may lie between the real camera and the point. If the real pixel is occluded in this way, it cannot contribute its color to the virtual pixel.

The basic approach is to run the depth search algorithm on a pixel from the real camera. If the recovered depth lies close enough in space to the 3D point computed for the virtual camera pixel, it is assumed the real camera pixel is not occluded - the color of this real pixel is allowed to contribute to the color of the virtual pixel. In practice, system speed is increased by immediately accepting points that are geometrically certain not to be occluded.

(c) Determining Virtual Pixel Color

After determining the depth of a virtual pixel and which cameras have an un-occluded view, all that remains is to combine the colors of real pixels to produce a color for the virtual pixel. The simplest method would be to choose the pixel from the closest camera. However, this produces sharp images that often contain visible borders where adjacent pixels were taken from different cameras. Pixel colors vary between cameras for several reasons. First, the cameras may have slightly different spectral responses. Second, the 3D model is not exact, and therefore the pixels from different cameras may not line up exactly. Third, unless the bi-directional reflectance distribution function is uniform, the actual reflected light will vary at different camera vantage points.

In order to compensate for these effects, the colors of several candidate pixels are averaged together. The simplest and fastest method is to take a straight average of the pixel color from the N closest cameras. This method produces results that contain no visible borders within the image. However, it has the disadvantage that it produces a blurred image even if the virtual camera is exactly positioned at one of the real cameras.

Hence, a weighted average is taken of the pixels from the closest N cameras, such that the closest camera is given the most weight. This method produces better results than either of the previous methods, but requires more substantial computation.

System Hardware and Software

Fourteen Sony DCX-390 video cameras were equally spaced around the subject, and one viewed him/her from above. (See Fig. 10, illustrating the system diagram and explaining that five computers pre-process the image to find the silhouettes and pass the data to the rendering server, the mixed reality machine takes the camera output from the head mounted display and calculates the pose of the marker, and this information is then passed to the rendering server that returns the appropriate image of the subject, which is rendered into the user's view in real time.). Five video-capture machines received data from three cameras each. Each video-capture machine had Dual 1GHz Pentium III processors and 2Gb of memory. The video-capture machines pre-process the video frames and pass them to the rendering server via gigabit Ethernet links. The rendering server had a 1.7 GHz Pentium IV Xeon processor and 2Gb of memory.

Each video-capture machine receives the three 640x480 video-streams in YCrCb format at 30Hz and performs the following operations on each:

(a) Each pixel is classified as foreground or background by assessing the likelihood that it belongs to a statistical model of the background. This model was previously generated from video-footage of the empty studio.

(b) Morphological operators are applied to remove small regions that do not belong to the silhouette.

(c) Geometric radial lens distortion is corrected for.

Since each foreground object must be completely visible from all cameras, the zoom level of each camera must be adjusted so that it can see the subject, even as he/she moves around. This means that the limited resolution of each camera must be spread over the desired imaging area. Hence, there is a trade-off between image quality and the volume that is captured.

Similarly, the physical space needed for the system is determined by the size of the desired capture area and the field of view of the lenses used. A 2.8 mm lens has been experimented with that provides approximately a 90 degree field of view. With this lens, it is possible to capture a space that is 2.5m high and 3.3m in diameter with cameras that are 1.25 meters away.

Calibration of Camera

In order to accurately compute the 3D models, it is necessary to know where a given point in the imaged space would project in each image to within a pixel or less. Both the internal parameters for each camera, and the spatial transformation between the cameras are estimated. This method is based on routines from Intel's OpenCV library. The results of this calibration are optimized using a robust statistical technique (RANSAC).

Calibration data is gathered by presenting a large checkerboard to all of the cameras. For our calibration strategy to be successful, it is necessary to capture many views of the target in a sufficiently large number of different positions. Intel's routines are used to detect all the corners on the checkerboard, in order to calculate both a set of intrinsic parameters for each camera and a set of extrinsic parameters relative to the checkerboard's coordinate system. This is done for each frame where the checkerboard was detected. If two cameras detect the checkerboard in the same frame, the relative transformation between the two cameras can be calculated. By chaining these estimated transforms together across frames, the transform from any camera to any other camera can be derived.

Each time a pair of cameras both see the calibration pattern in a frame, the transformation matrix is calculated between these camera positions. This is considered to be one estimate of the true transform. Given a large number of frames, a large number of these estimates are generated that may differ considerably. It is desired to combine these measurements to attain an improved estimate.

One approach would be to simply take the mean of these estimates, but better results can be obtained by removing outliers before averaging. For each camera pair, a relative transform is chosen at random and a cluster of similar transforms is selected, based on proximity to the randomly selected one. This smaller set is averaged, to provide an improved estimate of the relative transform for that pair of cameras. These stochastically chosen transforms are then used to calculate the relative positions of the complete set of cameras relative to a reference camera.

Since the results of this process are heavily dependent on the initial randomly chosen transform, it is repeated several times to generate a family of calibration sets. The "best" of all these calibration sets is picked. For each camera, the point at which the corners of the checkerboard are detected corresponds to a ray through space. With perfect calibration, all the rays describing the same checkerboard corner will intersect at a single point in space. In practice, calibration errors mean that the rays never quite intersect. The "best" calibration set is defined to be the set for which these rays most nearly intersect.

3-D INTERACTION FOR AR AND VR

The full system combines the virtual viewpoint and augmented reality software (see Fig. 10). For each frame, the augmented reality system identifies the transformation matrix relating marker and camera positions. This is passed to the virtual viewpoint server, together with the estimated camera calibration matrix. The server responds by returning a 374x288 pixel, 24bit color image, and a range estimate associated with each pixel. This simulated view of the remote collaborator is then superimposed on the original image and displayed to the user.

In order to support the transmission of a full 24bit color 374x288 image and 16 bit range map on each frame, a gigabit Ethernet link is used. The virtual view renderer operated at 30 frames per second at this resolution on average. Rendering speed scales linearly with the number of pixels in the image, so it is quite possible to render slightly smaller images at frame rate. Rendering speed scales sub-linearly with the number of cameras, and image quality could be improved by adding more.

The augmented reality software runs comfortably at frame rate on a 1.3 GHz PC with an nVidia GeForce II GLX video card. In order to increase the system speed, a single frame delay is introduced into the presentation of the augmented reality video. Hence, the augmented reality system starts processing the next frame while the virtual view server generates the view for the previous one. A swap then occurs. The graphics are returned to the augmented reality system for display, and the new transformation matrix is sent to the virtual view renderer. The delay ensures that neither machine wastes significant processing time waiting for the other and a high throughput is maintained.

Augmented Reality Conferencing

A desktop video-conferencing application is now described. This application develops the work of Billinghurst and Kato [M. Billinghurst and H. Kato, Real World Teleconferencing, In Proceedings of CHI'99 Conference Companion ACM, New York, 1999], who associated two-dimensional video-streams with fiducial markers. Observers could manipulate these markers to vary the position of the video streams and restore spatial cues. This created a higher feeling of remote presence in users.

In the present system, participant one (the collaborator) stands surrounded by the virtual viewpoint cameras. Participant two (the observer) sits elsewhere, wearing the HMD. The terms "collaborator" and "observer" are used in the rest of the description herein to refer to these roles. Using the present system, a sequence of rendered views of the collaborator is sent to the observer so that the collaborator appears superimposed upon a fiducial marker in the real world. The particular image of the collaborator generated depends on the exact geometry between the HMD-mounted camera and the fiducial marker. Hence, if the observer moves his head, or manipulates the fiducial marker, the image changes appropriately. This system creates the perception of the collaborator being in the three-dimensional space with the observer. The audio stream generated b y the collaborator is also spatialized so that it appears to emanate from the virtual collaborator on the marker.

For the present application, a relatively large imaging space (approx 3x3x2m) has been chosen, which is described at a relatively low resolution. This allows the system to capture movement and non-verbal information from gestures that could not possibly b e captured with a single fixed camera. The example of an actor auditioning for a play is presented. (See Fig. 11, a desktop 3-D augmented reality video-conferencing, which captures full body movement over a 3mx3m area allowing the expression of non-verbal communication cues.). The full range of his movements can be captured by the system and relayed into the augmented space of the observer. Subjects reported the feeling that the collaborator was a stable and real part of the world. They found communication natural and required few instructions.

Collaboration in Virtual Environments

Virtual environments represent an exciting new medium for computer-mediated collaboration. Indeed, for certain tasks, they are demonstrably superior to video-conferencing [M. Slater, J. Howell, A. Steed, D-P. Pertaub, M. Garau, S. Springel . Acting in Virtual Reality. ACM Collaborative Virtual Environments, pages 103-110, 2000]. However, it was not previously possible to accurately visualize collaborators within the environment and a symbolic graphical representation (avatar) was used in their place. Considerable research effort has been invested in identifying those non-verbal behaviors that are crucial for collaboration [J. Cassell and K.R. Thorisson. The power of a nod and a glance: Envelope vs. emotional feedback in animated conversational agents. Applied Artificial Intelligence, 13 (4-5): 519-539, June 1999] and elaborate interfaces have been developed to control expression in avatars.

In this section, the symbolic avatar is replaced with a simulated view of the actual person as they explore the virtual space in real time. The appropriate view of a collaborator in the virtual space is generated, as seen from our current position and orientation.

In order to immerse each user in the virtual environment, it is necessary to precisely track their head orientation and position, so that the virtual scene can be rendered from the correct viewpoint. These parameters were estimated using the Intersense IS900 tracking system. This is capable of measuring position to within 1.5mm and orientation to within 0.05 degree inside a 9x3m region at video frame rates. For the observer, the position and orientation information generated by the Intersense system is also sent to the virtual view system to generate the image of the collaborator and the associated depth map. This is then written into the observer's view of the scene. The depth map allows occlusion effects to be implemented using Z-buffer techniques.

Fig. 12 shows several frames from a sequence in which the observer explores a virtual art gallery with a collaborator, who is an art expert. (Fig. 12 illustrating interaction in virtual environments. The virtual viewpoint generation can be used to make live video avatars for virtual environments. The example of a guide in a virtual art gallery is presented. The subject can gesture to objects in the environment and communicate information by non-verbal cues. The final frame shows how the depth estimates generated by the rendering system can be used to generate correct occlusion. Note that in this case the images are rendered 640x480 pixel resolution at 30 fps.). The collaborator, who is in the virtual view system, is seen to move through the gallery discussing the pictures with the user. The virtual viewpoint generation captures the movement and gestures of the art expert allowing him to gesture to features in the virtual environment and communicate naturally. This is believed to be the first demonstration of collaboration in a virtual environment with a live, fully three-dimensional video avatar.

Tangible AR Interaction

One interesting aspect of the video-conferencing application was that the virtual content was attached to physical real-world objects. Manipulation of such objects creates a "tangible user interface" with the computer (see Fig. 6). In our previous application, this merely allowed the user to position the video-conferencing stream within his/her environment. These techniques can also be applied to interact with the user in a natural physical manner. For example, Kato et al. [H. Kato, M. Billinghurst, I. Poupyrev, K. Inamoto and K. Tachibana, Virtual Object Manipulation on a table-top AR environment. Proceedings of International Symposium on Augmented Reality, 2000] demonstrated a prototype interior design application in which users can pick up, put down, and push virtual furniture around in a virtual room. Other examples of these techniques are presented in I. Poupyrev, D. Tan, M. Billinghurst, H. Kato and H. Regenbrecht. Tiles: A mixed reality authoring interface. Proceedings of Interact 2001, 2001, M. Billinghurst, I. Poupyrev, H. Kato and R. May. Mixing realities in shared space: An augmented reality interface for collaborative computing. IEEE International Conference on Multimedia and Expo, New York, July 2000 and M. Billinghurst, I. Poupyrev, H. Kato and R. May, Mixing realities in shared space: An augmented reality interface for collaborative computing, IEEE International Conference on Multimedia and Expo, New York, July 2000.

The use of tangible AR interaction techniques in a collaborative entertainment application has been explored. The observer views a miniaturized version of a collaborator exploring the virtual environment, superimposed upon his desk in the real world. Fig. 13 illustrates a tangible interaction sequence, demonstrating interaction between a user in AR and collaborator in AR. The sequence runs along each row in turn. In the first frame, the user sees the collaborator exploring a virtual environment on his desktop. The collaborator is associated with a fiducial marker "paddle". This forms a tangible interface that allows the user to take him out of the environment.

The user then changes the page in a book to reveal a new set of markers and VR environment. This is a second example of tangible interaction. He then moves the collaborator to the new virtual environment, which can now be explored.

In the final row, an interactive game is represented. The user selects a heavy rock from a "virtual arsenal" using the paddle. He then moves it over the collaborator and attempts to drop it on him. The collaborator sees the rock overhead and attempts to jump out of the way. The observer is associated with a virtual "paddle." The observer can now move the collaborator around the virtual environment, or even pick him up and place him inside a new virtual environment by manipulating the paddle.

After M. Billinghurst, H. Kato and I. Poupyrev. The MagicBook: An interface that moves seamlessly between reality and virtuality. IEEE Computer Graphics and Applications, 21(3): 6-8, May/June 2001, the particular virtual environment is chosen using a real-world book as the interface. A different fiducial marker (or set thereof) is printed on each page and associated with a different environment. The observer simply turns the pages of this book to choose a suitable virtual world.

Similar techniques can be employed to physically interact with the collaborator. The example of a "cartoon" style environment is presented in Fig. 13. The paddle is used to drop cartoon objects such as anvils and bombs onto the collaborator, who attempts, in real time, to jump out of the way. The range map of the virtual view system allows us to calculate the mean position of the observer and hence implement a collision detection routine.

The observer picks up the objects from a repository by placing the paddle next to the object. He drops the object by tilting the paddle when it is above the observer. This type of collaboration between an observer in the real world and a colleague in a virtual environment is important and has not previously been explored.

Result

A novel shape-from-silhouette algorithm has been presented, which is capable of generating a novel view of a live subject in real time, together with the depth map associated with that view. This represents a large performance increase relative to other published work. The volume of the captured region can also be expanded by relaxing the assumption that the subject is seen in all of the cameras views.

The efficiency of the current algorithm permits the development of a series of live collaborative applications. An augmented reality based video-conferencing system is demonstrated in which the image of the collaborator is superimposed upon a three-dimensional marker in the real world. To the user the collaborator appears to be present within the scene. This is the first example of the presentation of live, 3D content in augmented reality. Moreover, the system solves several problems that have limited previous video-conferencing applications, such as natural non-verbal communication.

The virtual viewpoint system is also used to generate a live 3D avatar for collaborative work in a virtual environment. This is an example of augmented virtuality in which real content is introduced into virtual environments. As before, the observer always sees the appropriate view of the collaborator but this time they are both within a virtual space. The large area over which the collaborator can be imaged allows movement within this virtual space and the use of gestures to refer to aspects of the world.

Lastly, "tangible" interaction techniques is used to show how a user can interact naturally with a collaborator in a three-dimensional world. The example of a game whereby the collaborator must dodge falling objects dropped by the user is presented. A real world use could be an interior design application, where a designer manipulated the contents of a virtual environment, even while the client stood inside the world. This type of collaborative interface is as a variant of Ishii's tangible user interface metaphor [H. Ishii and B. Ulmer, Tangible bits: towards seamless interfaces between people, bits and atoms, In Proceedings of CHI 97. Atlanta, Georgia, USA, 1997].

The process and system of the present invention has been described above in terms of functional modules in block diagram format. It is understood that unless otherwise stated to the contrary herein, one or more functions may be integrated in a single physical device or a software module in a software product, or one or more functions may be implemented in separate physical devices or software modules at a single location or distributed over a network, without departing from the scope and spirit of the present invention.

3D Video Immersion Room

A preferred embodiment of the invention provides a "3D Video Immersion Room". As shown in Fig. 6 and described above, a user of the room would don a Head Mounted Display (HMD) with a camera attached. Upon entering the room, the user is able to experience a number of scenarios containing arbitrary combinations of (1) realistic live 3D video, (2) prerecorded 3D video, (3) virtual CG content, and (4) the actual room, people, and objects around them. Depending on the combination, the room allows for scenarios that fall broadly into the categories of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), allowing for arbitrary mixtures of real and virtual content in a fully immersive environment.

The user can move around in the room and view the content from any angle. The content appears as if it were completely natural 3D objects that are part of the environment.

Applications

The eventual applications for this technology are almost limitless. Imagine the following scenario:

> You open the door to a room marked 'Zaxel AnySpace'. An attendant hands you an HMD and a small backpack to wear and tells you that today you will be learning about ancient Rome. You put the HMD over your eyes and the once bare room now becomes an ancient Roman stadium. Two gladiators battle furiously in the foreground, while the crowd cheers loudly in the background. Everything you see and hear, particularly the actors and their actions, is realistic enough to really put you "in the moment." Although you cannot touch anything in

this scene, you see and hear it as if you are really there - the raucous crowd, the expressions on the faces of the gladiators. One gladiator is given a deathblow. He falls at your feet. Tigers are rushing toward you. It's all too real. You pull your HMD off and the room is again just a room. Your heart is racing. Only something this realistic - with 3D positional audio and life-like characters and props - could make you react as if it were real. Your friends have been watching the spectacle from outside the room. They burst out laughing when you exit the room. It seemed so real.

Schools have one basic need: to educate. Any tool that can assist in this need is useful. Science centers and museums need to educate and entertain while at the same time attracting an ever-increasing number of people to their facilities. Entertainment Parks need to provide the most groundbreaking entertainment experiences to keep attendance high. Training Centers have a mix of the needs to educate, entertain, and attract visitors.

All of these potential customers have some need to transport their visitor-customer-students into almost any 3D scenario imaginable (historical or otherwise) and allow them to interact with pre-recorded and live human participants (*i.e.*, a virtual tour guide or an actual classmate, remote or local) with a highly flexible and collaborative 3D video system.

Schools in areas where there are no cultural resources (museums, theaters, music halls) need similar resources to provide a balanced education.

Entertainment parks need new and more immersive methods for attracting visitors. Now that home entertainment systems (video games, DVD, HDTV) have achieved such a high level of quality, entertainment parks need an exponential leap to keep their "wow" factor. While hydraulic simulator rides and current primitive VR systems are successfully deployed in many entertainment parks, the next logical leap is an AR system.

MUSEUMS

The broader impacts are not just lower cost ways of doing currently feasible activities (going to the museum, for example), but rather an entirely new paradigm in human experience - blurring the line between visual reality and unreality. Museums currently house paintings and dinosaurs, why not experiences? The invention provides a way to capture/create and play back an experience: being in a Roman arena, being on a street in Medieval London, meeting the President. Imagine stepping into the Hall of Dinosaurs and seeing pterosaurs flying overhead. You look at the bones of that Brontosaurus and then all of a sudden the beast is as she was millions of years ago - with flesh and skin, steam rising from her nostrils. Little dinosaurs run underfoot, squealing and nipping at each other.

Museums (art, science, and natural history) will use 3D Immersion Rooms to add archives of videos so that visitors can have immersive experiences such as watching plays and musical performances, walking inside the wild forests of South America, or traveling inside the human body.

EDUCATION

Public school districts without access to museums and other cultural institutions could buy 3D Immersion Rooms and use the same courseware that museums use. If a teacher is teaching a lesson on Ancient Rome, the above gladiator scene that, say, the Smithsonian developed could be uploaded to the 3D Immersion Room in the underprivileged school district. Communities in outlying areas could use it as a resource as well.

ARTISTIC PERFORMANCE PRESERVATION AND REVIEW

The invention can provide a new paradigm in cultural preservation. Great performing artists will be captured in 3D and preserved for posterity in a form that is as lifelike as possible. The subtle nuance that plain video or plain audio cannot convey is recorded for all time. Imagine a future opera student having the chance to see Luciano Pavarotti's last performance. Imagine a student of acting having the chance to watch a monologue by Jeremy Irons or Robert DeNiro and be able to move about the scene and pause as needed - where is he holding his tension, how does he convey that emotion?

SPORTS TRAINING

Sports centers using 3D Immersion Rooms will allow precise review of a runner's gait as coaches walk around a 3D sprinter.

INDUSTRIAL DESIGN AND ENGINEERING

People will be able to collaborate on the prototyping of a new airplane seat - from inside a virtual airplane.

DISTANCE CORPORATE TRAINING

Customers have been complaining that the level of face-to-face customer service has been lacking. A subject matter expert can hold a virtual training class with customer service reps from around the country to determine best practices for improving the quality of customer service.

NEXT GENERATION TELECONFERENCE

Corporations can hold virtual board meetings that far surpass standard video conferencing. If the VP of Sales is not doing his job, the CEO can look him right in the eye, expressing his dissatisfaction with a mere glance.

MEDICAL AND HEALTHCARE

Those in the medical field can visualize and collaborate on problems in new and more useful ways. A patient can virtually visit a specialist in another country. Two researchers can visualize a human-sized model of a complex organic molecule - walk around it, move it around in 3D space, and point out relevant details to each other.

ENTERTAINMENT PARK ATTRACTIONS

Make the "Haunted House" even scarier. Ghosts fly over the visitors' heads while the walls seem to be on fire. Yikes!

System Description

Referring to Fig. 14, as described above, the Virtual Viewpoint system captures the 3D shape and appearance of real objects and actors. The system takes raw 2D video from 12 or more video cameras 1401 and creates 3D video the can be viewed from any viewpoint 1402. Sophisticated computer vision techniques are used to simultaneously derive the shape and appearance of any objects within the capture space, in real-time, based on the images from the cameras.

The system works by first segmenting each image into foreground and background components using a background subtraction technique, the simplest of which is chromakey (commonly known as blue-screen). The resulting foreground-only image is called a silhouette.

If the cameras are accurately calibrated (so that an exact mapping from global 3D coordinates to 2D image coordinates is known), then it is possible to compute an approximate 3D shape of the foreground objects using a technique called "silhouette intersection". Laurentini called the intersection thus derived the "visual hull" and derived the mathematical relationships governing the inaccuracy of this method, pointing out that the resulting 3D models may not be exact - even when theoretically given an infinite number of cameras. The method that can be used for deriving the visual hull in real-time is very similar to the method used by Matusik et al.

Once the visual hull has been computed, a number of 3D shape refinement techniques are possible. For example, for each point on the surface of the resulting model, it is possible to project it into the images from each camera and evaluate the consistency of the set of resulting pixel colors. If the colors are inconsistent (*i.e.*, it is improbable that any object would have that set of colors from those viewpoints), the point can be declared to be unoccupied and the 3D model refined based on that information. This technique is similar to the concept of Space Carving.

Once the approximate 3D shape of objects are known, a number of methods can be used to create novel 3D views of the object using the input video. These methods fall into a broad class known as Image-Based Rendering (IBR). The system supports a number of different pixel coloring algorithms from fast and inaccurate up to slow and accurate. The user can choose an algorithm based on the desired trade-off between frame rate and fidelity.

The Virtual Viewpoint system has two main features that distinguish it from competing methods of creating 3D content:

- Real-time. The system is able to capture the appearance and shape of objects and actors instantaneously.
- Reality-based. The 3D objects created by the Virtual Viewpoint system are derived directly from video, so they have a realistic appearance. Actors can walk into the invention's capture studio and be instantly available as full 3D objects viewable from any direction. The 3D objects have the clothing, facial expressions, gait, equipment, etc., that the actor brings with him into the studio.

Camera Tracking

The invention tracks the location of the user and the direction he is looking. There are many commercial head-tracking systems available that can be used to measure the user's 3D position and orientation (*e.g.*, systems from Metamotion of San Francisco, CA, Polhemus of Colchester, VT, Ascension Technology Corp. of Burlington, VT, and Intersense, Inc., of Burlington, MA). The invention provides a new tracking system that uses a cheap video camera attached to the user's HMD and a set of visible markers in the room. This has the following advantages over existing systems:

- Inexpensive. Relatively high quality, cheap, compact security cameras are available for around $200. The markers can be printed out using a computer and laser printer.
- Easy to set up and calibrate. The user can attach the markers to the walls of any room and calibrate the system in a few minutes simply by looking slowly around the room while the system detects and links the markers.
- Video available for AR. The video from the camera can be displayed to the user, allowing for Augmented Reality applications with no extra hardware. 3D content that is introduced over the real video is guaranteed to be aligned properly.
- Multiple simultaneous users in the same room. Each additional user in the room only needs an HMD with an attached camera; they can use the same set of markers to view the same (or different) scenes.
- Passive sensing. Many of the existing commercial head-tracking devices use IR or radio frequency emitters, which may interfere with each other or other nearby devices.
- Accuracy. A camera-based system can produce very accurate orientation results (around 0.1 degrees, depending on the lens and sensor used), with somewhat less accurate positioning results.
- Reliability. Video camera technology is used in mission-critical applications every day. Off-the-shelf components are extremely reliable with very long MTBF.
- Other Applications. A camera by itself (without an HMD) can be used to track the position of other objects. Given the small size of such cameras, they can be attached to almost anything - if attached to a wand, the location and orientation of the wand can be computed, allowing the wand's use as a user interface device.

Using this head-tracking system, the invention can attach any 3D content to a fixed position in the world and render the content as it should look from the position of the user. For example, it would be easy to merge the real imagery from the camera with Virtual Viewpoint content and CG content to create a truly immersive AR or VR experience such as that described in the Ancient Rome scenario,above.

Some related work has already done by Billinghurst, et al., at the University of Washington. They have used an HMD with an attached camera to detect the position of a 2D marker relative to the camera and embed 3D content at that location in the scene. With respect to Fig. 15, we have modified their software (called "AR Toolkit") to display Virtual Viewpoint content in an Augmented Reality scenario 1501, 1502.

The AR Toolkit marker tracking works by using very simple image processing techniques to determine the corners of the target and some complex math to determine the six Degrees of Freedom (DOF) pose of the camera relative to the marker. The set of markers that are used are planar black and white images. Each marker consists of a black square border on a white background. Inside the border is a unique pattern intended to distinguish the markers from each other, for example a set of Greek letters.

To describe the algorithm in brief, the camera image is thresholded and contiguous dark areas are identified using a connected components algorithm. A contour seeking technique identifies the outline of these regions. Contours that do not contain exactly four corners are discarded. The corner positions are estimated by fitting straight lines to each edge and determining the points of intersection of these lines.

A projective transformation is used to map the enclosed region to a standard shape. The resulting image is then cross-correlated with stored patterns to establish the identity and orientation of the marker in the image. For a calibrated camera, the image positions of the marker corners uniquely identify the three-dimensional position and orientation of the marker in the world. This information is expressed as a Euclidean transformation matrix relating the camera and marker coordinate systems and is used to render the appropriate view of the virtual content into the scene.

The AR Toolkit also supports detecting and identifying multiple markers simultaneously in the same image. This capability is primarily used to overcome problems caused when a marker is not completely visible, either because another object obscures it or because it is not completely within the field of view of the camera.

The AR Toolkit algorithm has several shortcomings that has to be overcome. First, its multiple marker detection strategy uses a computation time that grows linearly with the number of potential markers. Secondly, its algorithm exhibits relatively high rates of failure to detect a target that is present (false negative) and detection of a non-existent target (false positive). Finally, the algorithm has an instability when the target is viewed from the top down.

The invention allows a large number of independent markers to be detected, identified, and calibrated relative to each other with performance at video frame rate. After this has been accomplished, the presence of any single marker within the field of view of the camera is sufficient to determine the camera's position and orientation within the room and to render 3D content appropriately as if it were seamlessly attached to the environment.

The invention provides a system of markers and marker detection software that supports a large number of independent markers. The markers are:

- Easy to detect robustly and accurately.
- Easy to distinguish from each other with a low error rate.

While the AR Toolkit system theoretically supports an arbitrary number of markers, the processing time grows linearly with the number of possible markers to be detected. It also occasionally detects markers even when they are not present in the image (false positive detections).

The invention provides a method to design a large set of markers for maximum detectability and distinguishability. In particular, a pattern other than a black square, or one involving a full range of color, improves the speed and/or reliability of the system.

The invention can detect and identify a large set (preferably 50 or more) of distinct markers (targets) at video frame rate (preferably 30 fps). An automated calibration system is provided so that the markers can be quickly attached to the walls of any room and calibrated so that the system can be set up and used within a few minutes.

The invention was validated using the following steps:

1. Design a set of 50 distinct targets detectable by the marker detection algorithm. Attach these targets to the wall of a room in carefully measured locations.
2. Develop an application using the algorithm to detect and identify these targets using a camera. The application is instrumented to highlight and label the targets that are detected.
3. Perform a series of experiments where the camera is pointed and scanned over the wall from different vantage points. The video from the camera is recorded to disk on a computer.
4. Run the algorithm offline on each frame of the video. An observer examines the results for each frame and identifies each time the algorithm fails to detect a marker

(false negative), detects a marker that is not present (false positive) or identifies a marker incorrectly.

5. From the results of the experiments, compute false negative, false positive, and misidentification rates. When multiple markers are correctly identified in a single frame, compare the measured and computed translation between the markers to evaluate the accuracy of the computed 3D positions. Measure the detection speed.
6. Using the recovered marker positions from the experimental data, develop a robust least-squares approach for combining the data into an accurate set of marker positions and orientations in a global coordinate system, thus calibrating the system. The derived results can be compared to the measured ground truth.
7. With the results from step 6, a fully calibrated system was developed that allows 3D content to be rendered as if it were attached to the wall.

Referring to Fig. 16, a system overview is shown. An HMD 1601 is provided to the user. The HMD 1601 has an integrated video camera 1602 and video display 1603. The video camera 1602 is used to detect targets within the Immersion Room.

The computer 1607 receives the video camera's 1602 signal via a wireless link 1605, 1608. The computer 1607 performs the target detection algorithm. The computer 1607 is calibrated to determine the relative positioning of the targets within the room to each other. During normal use, the computer 1607 detects the targets to calculate the user's position in the room.

The user's position is used by the computer 1607 to determine the viewing angle and positioning within the video being played to the user through the video goggles 1603. The location of the camera in the 3D world (and thus the location of the HMD 1601) can be determined accurately if the positions of the markers in the 3D world are known. This location is then used to render arbitrary 3D content as if it was attached to the world coordinate system. This content can be overlaid on top of the original camera video (so that the content appears to be a realistic part of the real-world scene). Alternatively, the virtual content can replace the real-world scene with a completely virtual scene that appears realistic because the viewpoint changes naturally as the wearer moves around in the world. The computer 1607 changes the positioning and angle of the video in real time and transmits the 3D video content to the video goggles 1603.

The video goggles 1603 receive the 3D video content from the computer 1607 via a wireless link 1606, 1604.

With respect to Fig. 17, the invention overlays 3D video content onto real time camera images. A camera 1701 sends a video signal to an image digitizer 1702. The image digitizer 1702 signal is used for detection of targets within the camera view 1703. The targets within the camera view are detected 1704.

The positioning of the detected targets is calculated within 3D space 1705. The 3D position of the user is now known and 3D content is rendered from the computed position 1706.

The original digitized image is composited with the rendered 3D content 1707. The 3D content is overlayed onto the original digitized image and displayed on the HMD 1708.

As one skilled in the art will readily appreciate, an HMD is not a required part of the invention. For example, the invention can easily be used with only a video camera where the system tracks the location of the video camera within an environment.

The calibration of the positioning of the targets relative to each other allows the position of the camera to be derived if any single target can be viewed. The calibration results are used to attach 3D content to a global coordinate system.

Targets

The targets must be distinguishable both when the camera is close to the target (and the target almost fills the image) and when it is far away (and thus is a very small fraction of the image). It is clear that for any given target size and camera position, there will be a range limit beyond which the target will not be identifiable regardless of the target detection algorithm (for example, at some extreme range the target will be smaller than a single pixel in the image). In fact, the size of the target in the image is proportional to the size of the actual target and the focal length of the lens, and inversely proportional to the range. From an algorithmic standpoint, a small target that is close is indistinguishable from a large target that is far away.

The invention's target algorithm functions in two steps: target detection followed by target identification. The first step detects that a target is present by detecting the outline of the target (for example, a black square). The second step takes the detected target and identifies its orientation as well as which target it is (based on the design inside the square). The detection results along with the orientation are used to compute an estimate of the 3D transformation between the target and the camera.

The pattern inside the target can be thought of as an image at some particular resolution. In order to make the problem tractable, a very low resolution of 5x5 black-and-white pixels is preferred, although the number of pixels can be optimized for a specific application. The 5x5 pixel layout provides 2^25 (roughly 32 million) different possible targets, which is a sufficient number from which to choose 50 maximally distinguishable targets. The software is implemented such that larger target resolutions may be considered, although a longer running time will be required to find the optimal set. Since the limiting accuracy of the system is achieved when the target is small in the image, it does not make sense to consider a set of targets with very high resolution, since much of the detail of those targets will be indistinguishable when the target is small, unless the target remains at a fixed size for a particular application.

In addition to each target being distinct from the others, it must also be distinct from the rotated versions of itself, since its orientation is important in computing the 3D transformation between target and camera. Thus, of the 2^25 possible patterns at the example resolution, the ones that display 90-degree or 180-degree rotational symmetry or near-symmetry are unsuitable.

The process of selecting an optimal set of targets simplifies to the problem of finding a set of targets that are maximally different when compared to each other. Furthermore, if it is assumed that the effects of image noise do not bias the results (since image noise is generally zero-mean), therefore, one only needs to count how many pixels are different between the binary-valued black-and-white templates.

A Monte Carlo method is employed to search for an optimal set of targets. The method chooses a set of targets at random (with some restrictions) and considers each pair of targets in turn (including four orientations for each target), counting the number of pixels that are different. The count of different pixels is the score for each target pair. Since a set of targets is not better than its worst pair, the lowest score is used as an overall score for the entire set of targets. Fig. 18 shows an exemplary set of 50 targets with the best score of seven.

Referring to Fig. 19, a target detection test application program is provided that detects and identifies the target in each image. A sample view from the application is shown 1901. The test application outlines each target in the image with a color that represents the certainty with which it has been identified 1903. The target number is displayed over the target itself 1902. With a set of 50 targets, the unoptimized application runs at about 10-30 fps on a 2.0 GHz Pentium 4 computer. The test application automatically outputs the detection results including the confidence of each detection, target size, etc. The test application allows manual verification of selected targets.

The size of a target in the image affects how easily it is detected. Target size in the image is proportional to the distance from the camera. Of course, the exact camera distance that produces a particular image size depends on the physical size of the targets. The target size should be chosen based on the dimensions of the room, such that the targets appear sufficiently large from the likely camera positions.

When the width of the targets averaged ten pixels or less, none of the targets were detected. When the targets averaged 40 pixels wide or more, they were all detected. Between those sizes, detection rate varied with target size.

Round dots can be used in the target patterns instead of square ones to reduce the chance of erroneous target detection, or the targets or the algorithm can be modified in other simple ways depending on the intended application. For example, color could be used to differentiate target borders from target interiors.

With respect to Fig. 20, the targets 2002, 2003 are attached to the walls of a room 2001 such that at least one marker is always visible to the camera. With such a configuration, the camera position can be accurately tracked regardless of the direction of the user's gaze.

Auto Calibration

Typically, only when multiple targets are detected simultaneously can their positions be compared. When two targets are detected in the same video frame, a transform matrix representing the position of one target relative to the other target is derived from the positions of each target relative to the camera.

The target-to-target transforms are collected from many video frames as the camera is moved to various positions around the room in order to have as many samples as possible of each transformation.

When each possible pair of targets has been seen together a certain (configurable) number of times, the system analyzes the results and attempts to create a consistent chain of transforms linking all the targets, so that the position of each one can be determined relative to each of the others. This algorithm proceeds by selecting a random set of transforms that connects all of the targets to each other. Then the set of transforms is evaluated by looking at each frame of the video and using the transform set and the detected location of each target to predict the locations of the other detected targets in the image. The errors between predicted and actual locations are summed over the entire set of target pairs and frames. This sum is used as a score to evaluate the quality of the transform set. The set with the best score is typically selected.

Referring to Fig. 21, a calibration flowchart is shown. The video signal from the video camera 2101 on the HMD is captured 2102. The targets in the image are detected 2103. If the desired number of targets are not found 2104, the system resamples the video signal. If enough targets are found 2104, then the selection of pairs of targets begins by selecting a pair of targets from the image 2105.

The selected pair of targets are identified 2106, 2108 and the position of each target is calculated relative to the camera 2107, 2109. The position of each target is then calculated in relation to each other 2110.

The position of the target pair are added to the list of relative target transforms 2111.

The target pair processing is repeated until all target pairs in the image are processed 2112. If the captured image has completed the processing stage 2113, then the optimal set of transforms is calculated 2114 and the set of targets and transforms are output 2115. Otherwise, the process repeats until the image is processed 2113.

The detection algorithm detects the effects of viewing angles and gives higher weight to targets that are detected at more reliable angles.

False positive detections (detection of targets that aren't really there) and misidentifications (mistaking one target for another) introduce bad data into the calibration system. Setting the detection confidence threshold properly serves to discard the vast majority of these bad detections. Generally, 49 transforms are chosen in order to connect together the 50 targets in this example. Even with a 1% rate for bad detections, each random choice of a set of 49 transforms has only a 60% chance of containing no bad data. An additional stage of analysis can be added to the auto calibration algorithm to discard outliers – data that are inconsistent with the bulk of the collected data. This should virtually ensure an accurate transform chain, given enough collected position samples.

The auto calibration algorithm is a reasonably robust system based on random sampling. Instead of simply selecting pairs of transforms between two targets to incorporate into the transform chain, a small number of similar transforms can be randomly selected and combined to average out any zero-mean variability. Given that errors are compounded when multiple transforms are chained together, a random selection of a transform set should be biased toward generating a set of transforms with the minimal amount of chaining. The selection process could also be biased away from known trouble spots, such as when the target is seen directly head-on. In addition, the scoring system for transform sets takes into account the possible existence of outliers to prevent biasing the results away from an otherwise correct set of transforms.

After the system has been calibrated and the virtual content is being displayed, there is less data to work with – the camera position must be determined for each frame, from the targets detected in that frame. There are several additional steps that can be taken during this stage to ensure that the results are as good as possible. If several targets are detected, their relative detected positions can be compared to their relative positions as predicted by the transform chain, and any targets that do not appear where they are expected can be ignored. If, after this analysis, multiple good detections are still present, then they can be combined mathematically to produce a result that has a higher confidence than any of the individual detections.

Some frames are likely to have insufficient reliable data to correctly determine the camera location. To reduce the visible results of this, the camera movement over several frames can be extrapolated to predict the position in a new frame, on the assumption that a head-mounted camera's movement will be relatively smooth. This prediction could be used instead of the detected position if the number or quality of detections is low. With this "temporal smoothing" approach, the visible results are improved.

The detection algorithm thresholds the intensity of the full-color video image before doing the preliminary stages of target detection. This is done using a fixed brightness threshold; everything brighter than that is "white" and everything darker is "black". Because of this fixed threshold, a very bright or very dark image may cause this portion of the algorithm to give bad results, resulting in failed detections. Proper adjustment of the camera's shutter speed and iris opening, and of the algorithm's brightness threshold, will usually prevent this problem in an evenly lit room, but not all rooms are evenly lit. The system adaptively calculates the appropriate brightness threshold for a particular image or even for each subregion within a single image, rather than using a fixed threshold.

Targets are optimally placed so that the largest possible workspace is available in which at least one target is visible at an appropriate resolution and viewing angle.

With respect to Fig. 22, a task viewpoint of the invention is shown. The Process Video Input module 2201 receives video signals and forwards them to the requesting module. the Calibrate Targets module 2202 performs the calibration of the target within the room and calculates and stores target-to-target transforms 2203.

Once the calibration of the targets is complete, the system goes into normal user mode. During normal user mode, video signals pass from the Process Video Input module 2201 to the Calculate User Position module 2205. The Calculate User Position module 2205 passes images to the Determine Target Positions module 2204. The Determine Target Positions module 2204 calculates the position of targets detected in the images using the target-to-target transforms 2203.

Once the target positions have been calculated, the Calculate User Position module 2205 determines the user position within the environment. The Calculate User Position module 2205 passes the user positioning information to the Render Video Viewpoint module 2206.

The Render Video Viewpoint module 2206 dynamically streams 3D content video from the Video Library 2207 to the user through the Output Video module 2208. When the user changes his viewpoint, the information from the Calculate User Position module 2205 is used to change the position and angle of the 3D content. The 3D content is repositioned by the Render Video Viewpoint module 2206 and streamed to the Output Video module 2208 which displays the 3D content to the user via a display.

Although the invention is described herein with reference to the preferred embodiment, one skilled in the art will readily appreciate that other applications may be substituted for those set forth herein without departing from the spirit and scope of the present invention. Accordingly, the invention should only be limited by the Claims included below.

CLAIMS

1. A process for a immersing a user in a three dimensional virtual reality environment room, comprising the steps of:

providing a head mounted display worn by a user;

wherein said head mounted display comprises a video camera and video display;

providing a plurality of target markers;

distributing said plurality of target markers within said room;

wherein each of said plurality of target markers are distinct from all other target markers in said plurality of target markers and distinct from rotated versions of itself;

receiving a video signal of a portion of said room from said video camera;

identifying at least one target marker in said video signal;

calculating user position within said room using relative positioning of identified target marker(s);

streaming three dimensional video content to the user through said video display; and

dynamically repositioning the user's perspective viewpoint within said three dimensional video content by using said calculated user position to adjust position and viewing angle within said three dimensional video content.

2. The process of Claim 1, further comprising the step of:

providing target marker calibration means for automatically calibrating relative positions of said plurality of target markers within said room.

3. The process of Claim 2, wherein said target marker calibration means detects said plurality of target markers in said room using said video signal, and wherein said target marker calibration means identifies pairs of target markers within said room.

4. The process of Claim 3, wherein said target marker calibration means determines positioning of each target in a target pair relative to said video camera, wherein said target marker calibration means calculates positioning of each target in a target pair relative to each other, and wherein said target marker calibration means stores the relative positioning of the target pair in a list of relative target transforms.

5. The process of Claim 4, wherein said calculating user position step determines the relative positioning of identified target markers using said relative target transforms.

6. The process of Claim 5, wherein said calculating user position step detects the effects of viewing angles and gives higher weight to target markers that are detected at more reliable angles.

7. The process of Claim 1, wherein said receiving step receives said video signal via a wireless link.

8. The process of Claim 1, wherein said streaming step streams said three dimensional video content to the user through said video display via a wireless link.

9. The process of Claim 1, wherein said streaming step overlays said three dimensional video content onto said video signal and sends a resulting combined signal to said video display.

10. The process of Claim 1, wherein said plurality of target markers are a sufficient number such that at least one target marker is always visible in said video signal.

11. An apparatus for a immersing a user in a three dimensional virtual reality environment room, comprising:

a head mounted display worn by a user;

wherein said head mounted display comprises a video camera and video display;

a plurality of target markers;

means for distributing said plurality of target markers within said room;

wherein each of said plurality of target markers are distinct from all other target markers in said plurality of target markers and distinct from rotated versions of itself;

a module for receiving a video signal of a portion of said room from said video camera;

a module for identifying at least one target marker in said video signal;

a module for calculating user position within said room using relative positioning of identified target marker(s);

a module for streaming three dimensional video content to the user through said video display; and

a module for dynamically repositioning the user's perspective viewpoint within said three dimensional video content by using said calculated user position to adjust position and viewing angle within said three dimensional video content.

12. The apparatus of Claim 11, further comprising:

target marker calibration means for automatically calibrating relative positions of said plurality of target markers within said room.

13. The apparatus of Claim 12, wherein said target marker calibration means detects said plurality of target markers in said room using said video signal, and wherein said target marker calibration means identifies pairs of target markers within said room.

14. The apparatus of Claim 13, wherein said target marker calibration means determines positioning of each target in a target pair relative to said video camera, wherein said target marker calibration means calculates positioning of each target in a target pair relative to each other, and wherein said target marker calibration means stores the relative positioning of the target pair in a list of relative target transforms.

15. The apparatus of Claim 14, wherein said calculating user position module determines the relative positioning of identified target markers using said relative target transforms.

16. The apparatus of Claim 15, wherein said calculating user position module detects the effects of viewing angles and gives higher weight to target markers that are detected at more reliable angles.

17. The apparatus of Claim 11, wherein said receiving module receives said video signal via a wireless link.

18. The apparatus of Claim 11, wherein said streaming module streams said three dimensional video content to the user through said video display via a wireless link.

19. The apparatus of Claim 11, wherein said streaming module overlays said three dimensional video content onto said video signal and sends a resulting combined signal to said video display.

20. The apparatus of Claim 11, wherein said plurality of target markers are a sufficient number such that at least one target marker is always visible in said video signal.

21. A process for tracking a video camera in a three dimensional virtual reality environment room, comprising the steps of:

providing a video camera movable within said room;

providing a plurality of target markers;

distributing said plurality of target markers within said room;

wherein each of said plurality of target markers are distinct from all other target markers in said plurality of target markers and distinct from rotated versions of itself;

receiving a video signal of a portion of said room from said video camera;

identifying at least one target marker in said video signal; and

calculating video camera position within said room using relative positioning of identified target marker(s).

22. The process of Claim 21, further comprising the step of:

providing target marker calibration means for automatically calibrating relative positions of said plurality of target markers within said room.

23. The process of Claim 22, wherein said target marker calibration means detects said plurality of target markers in said room using said video signal, and wherein said target marker calibration means identifies pairs of target markers within said room.

24. The process of Claim 23, wherein said target marker calibration means determines positioning of each target in a target pair relative to said video camera, wherein said target marker calibration means calculates positioning of each target in a target pair relative to each other, and wherein said target marker calibration means stores the relative positioning of the target pair in a list of relative target transforms.

25. The process of Claim 24, wherein said calculating video camera position step determines the relative positioning of identified target markers using said relative target transforms.

26. The process of Claim 25, wherein said calculating video camera position step detects the effects of viewing angles and gives higher weight to target markers that are detected at more reliable angles.

27. The process of Claim 21, wherein said receiving step receives said video signal via a wireless link.

28. The process of Claim 21, wherein said plurality of target markers are a sufficient number such that at least one target marker is always visible in said video signal.

29. An apparatus for tracking a video camera in a three dimensional virtual reality environment room, comprising:

a video camera movable within said room;

a plurality of target markers;

means for distributing said plurality of target markers within said room;

wherein each of said plurality of target markers are distinct from all other target markers in said plurality of target markers and distinct from rotated versions of itself;

a module for receiving a video signal of a portion of said room from said video camera; and

a module for identifying at least one target marker in said video signal;

a module for calculating video camera position within said room using relative positioning of identified target marker(s).

30. The apparatus of Claim 29, further comprising:

target marker calibration means for automatically calibrating relative positions of said plurality of target markers within said room.

31. The apparatus of Claim 30, wherein said target marker calibration means detects said plurality of target markers in said room using said video signal, and wherein said target marker calibration means identifies pairs of target markers within said room.

32. The apparatus of Claim 31, wherein said target marker calibration means determines positioning of each target in a target pair relative to said video camera, wherein said target marker calibration means calculates positioning of each target in a target pair relative to each other, and wherein said target marker calibration means stores the relative positioning of the target pair in a list of relative target transforms.

33. The apparatus of Claim 32, wherein said calculating video camera position module determines the relative positioning of identified target markers using said relative target transforms.

34. The apparatus of Claim 33, wherein said calculating video camera position module detects the effects of viewing angles and gives higher weight to target markers that are detected at more reliable angles.

35. The apparatus of Claim 29, wherein said receiving module receives said video signal via a wireless link.

36. The apparatus of Claim 29, wherein said plurality of target markers are a sufficient number such that at least one target marker is always visible in said video signal.

Fig. 1

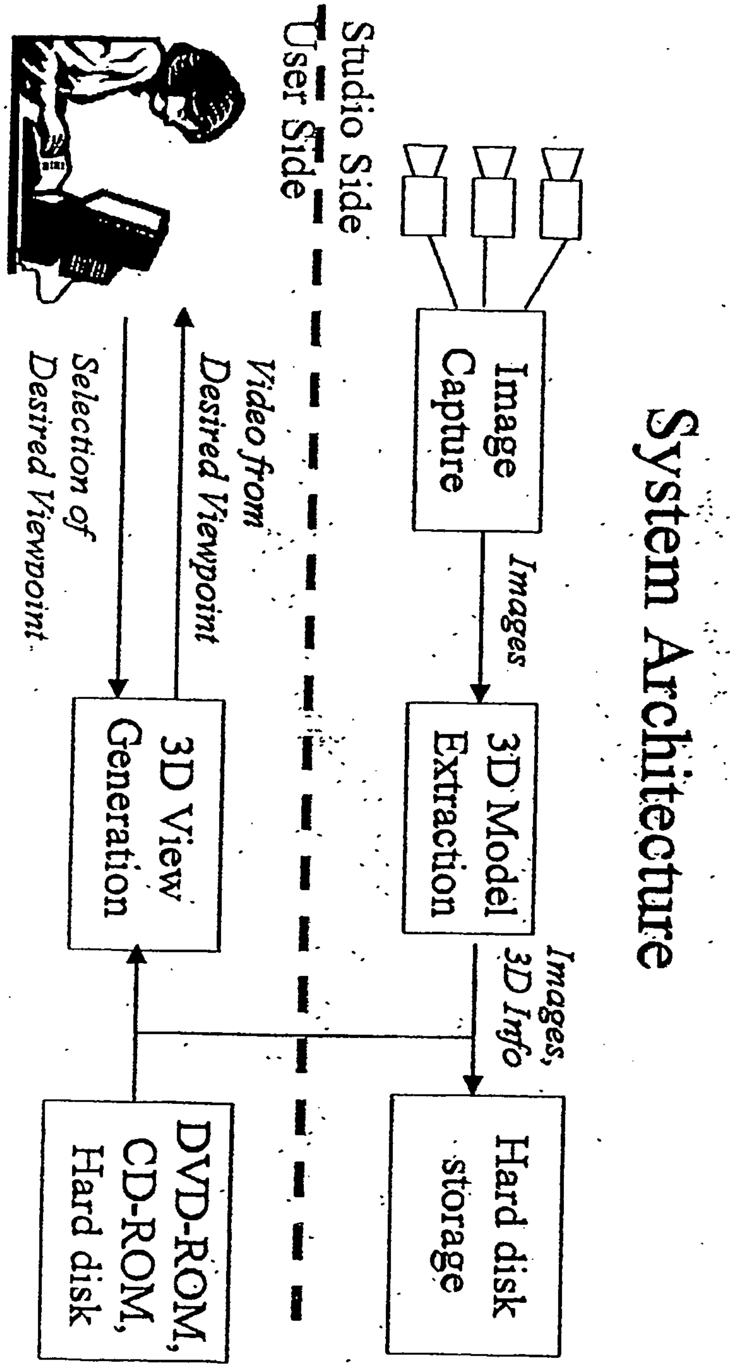

System Architecture
Image Capture
Images
3D Model Extraction
Images, 3D Info
Hard disk storage
Studio Side
User Side
Video from Desired Viewpoint
Selection of Desired Viewpoint
3D View Generation
DVD-ROM, CD-ROM, Hard disk

Fig. 2

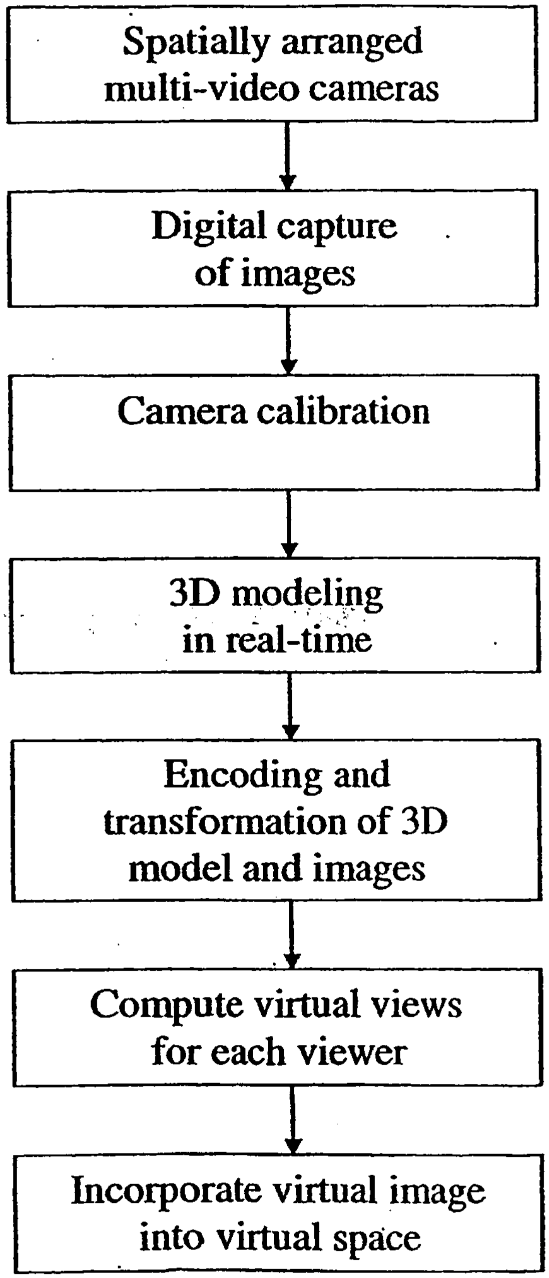

Spatially arranged multi-video cameras
Digital capture of images
Camera calibration
3D modeling in real-time
Encoding and transformation of 3D model and images
Compute virtual views for each viewer
Incorporate virtual image into virtual space

Fig. 3

View Generation Method

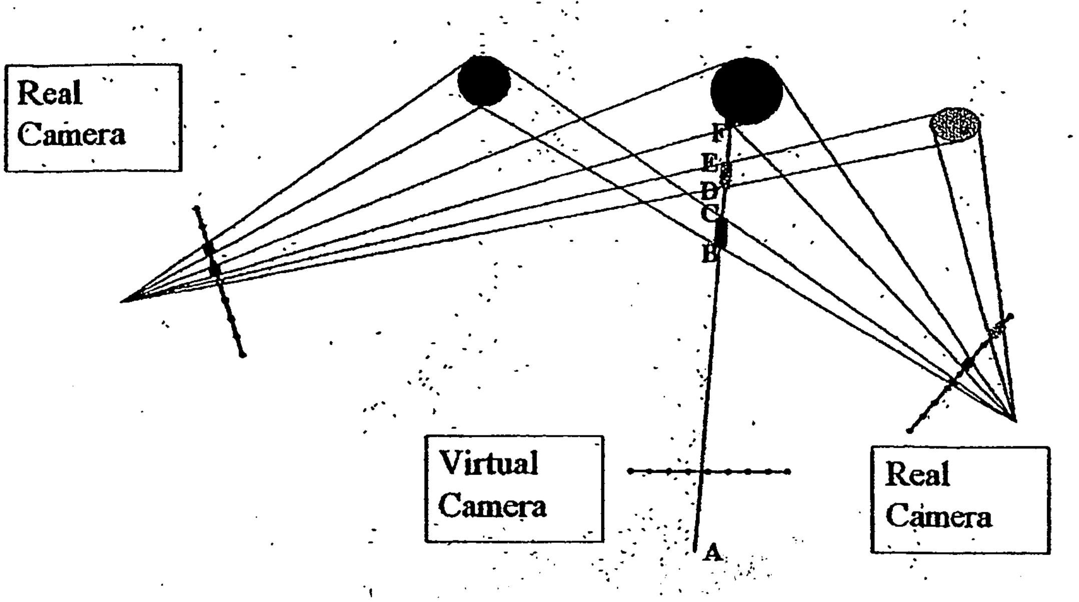
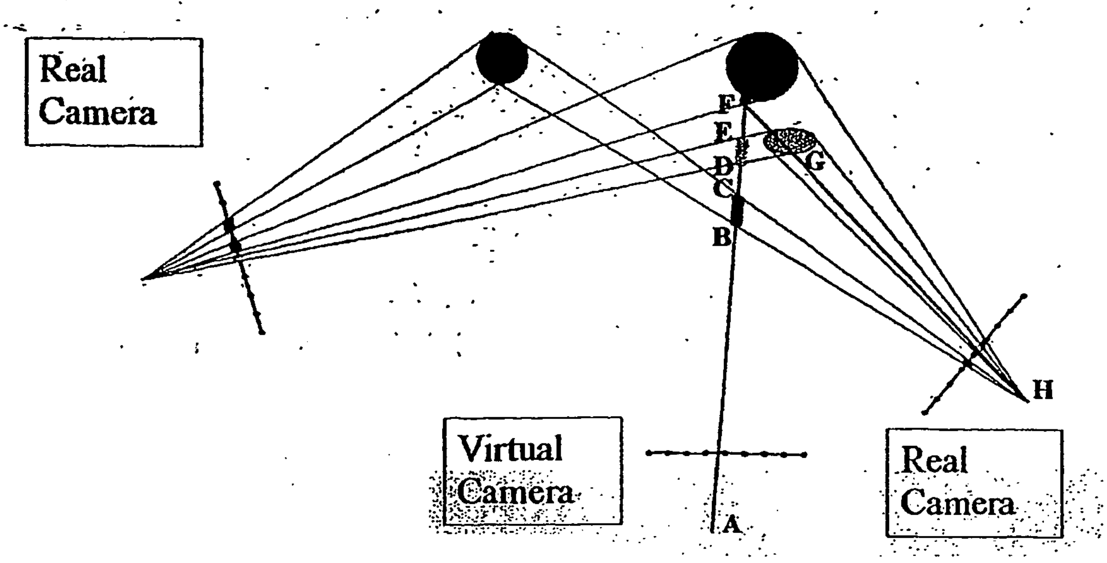


Fig. 4

Occlusion Problem



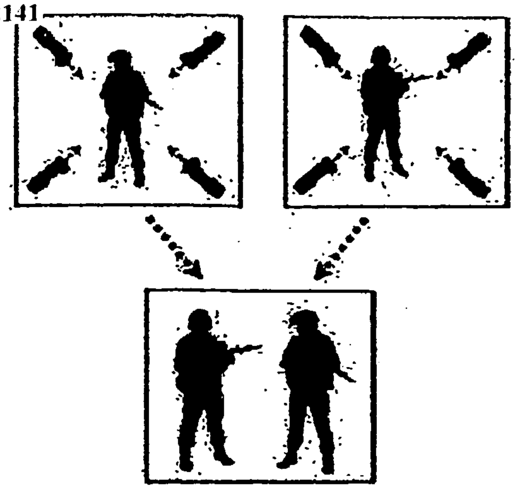


Fig. 6

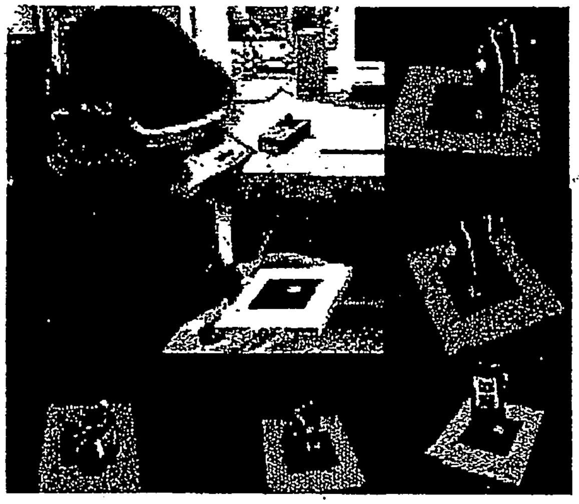
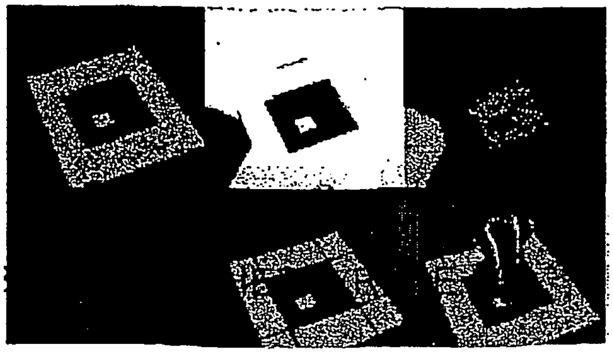


Fig. 7



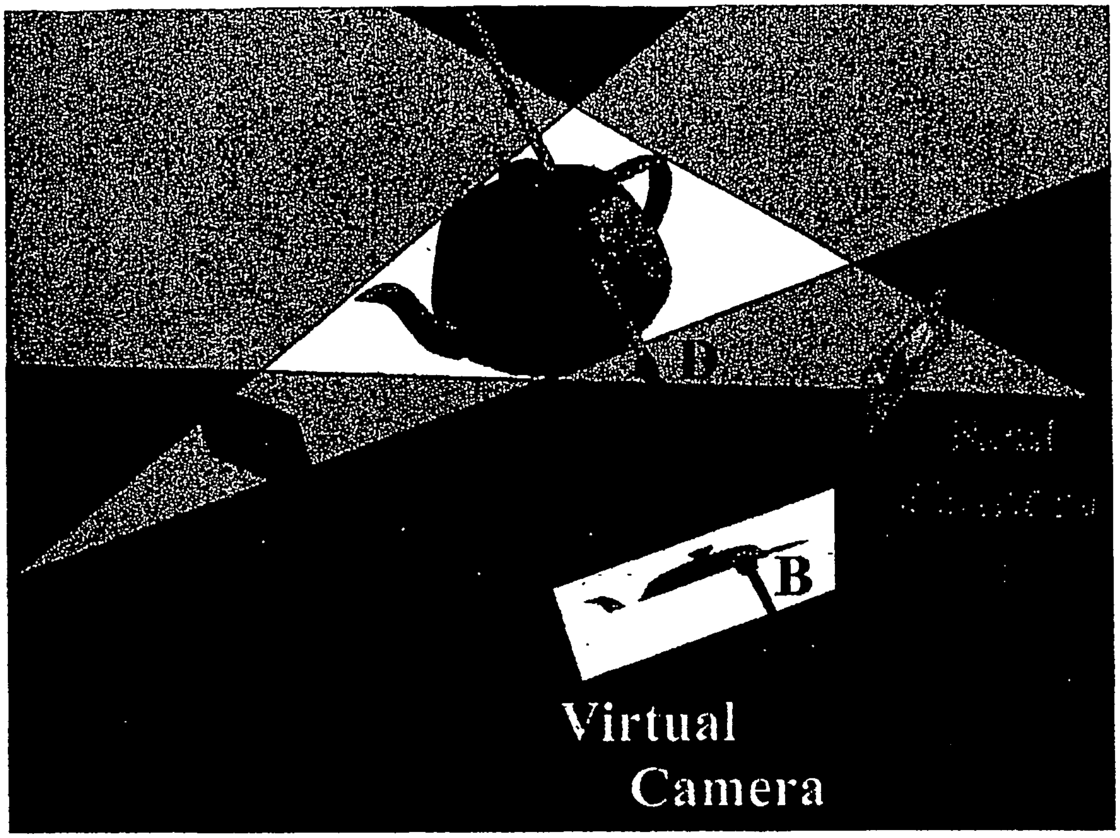

D
Real
Camera
B
Virtual
Camera

Fig. 9

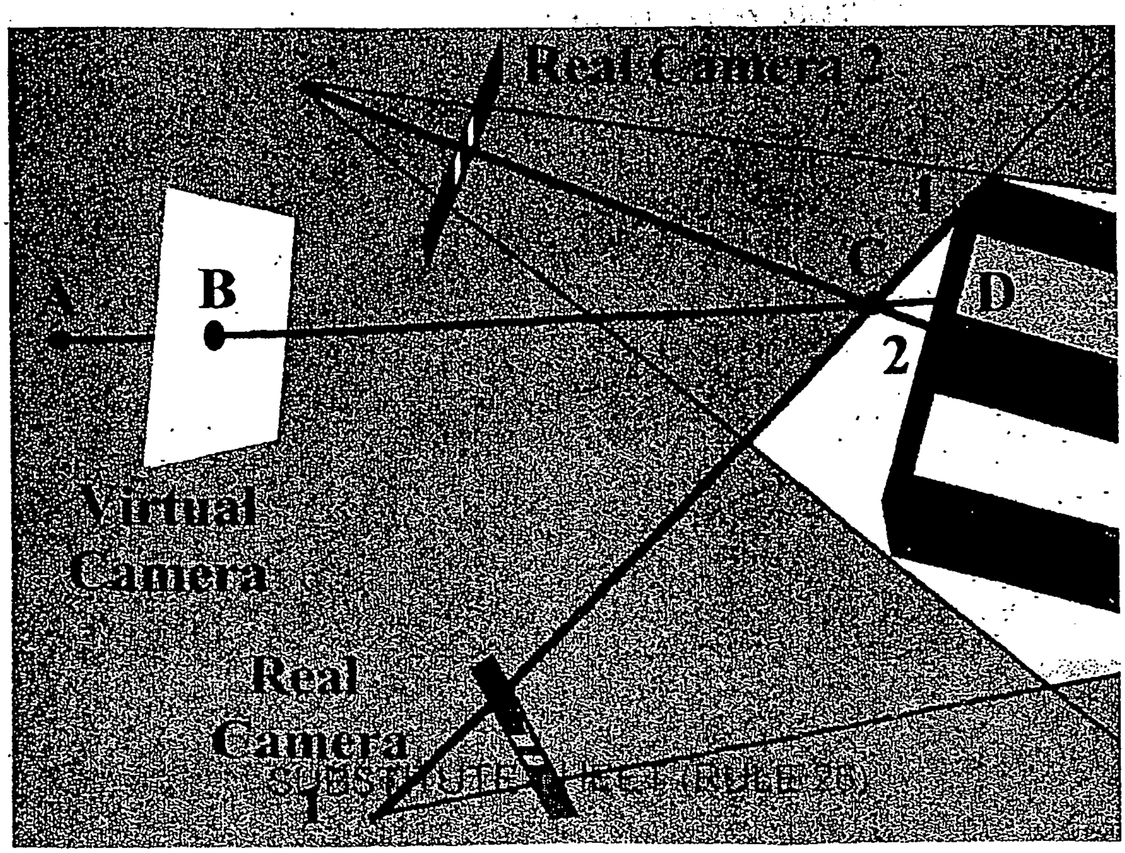

Real Camera 2
1
C
D
2
A
B
Virtual
Camera
Real
Camera
1

Fig. 10

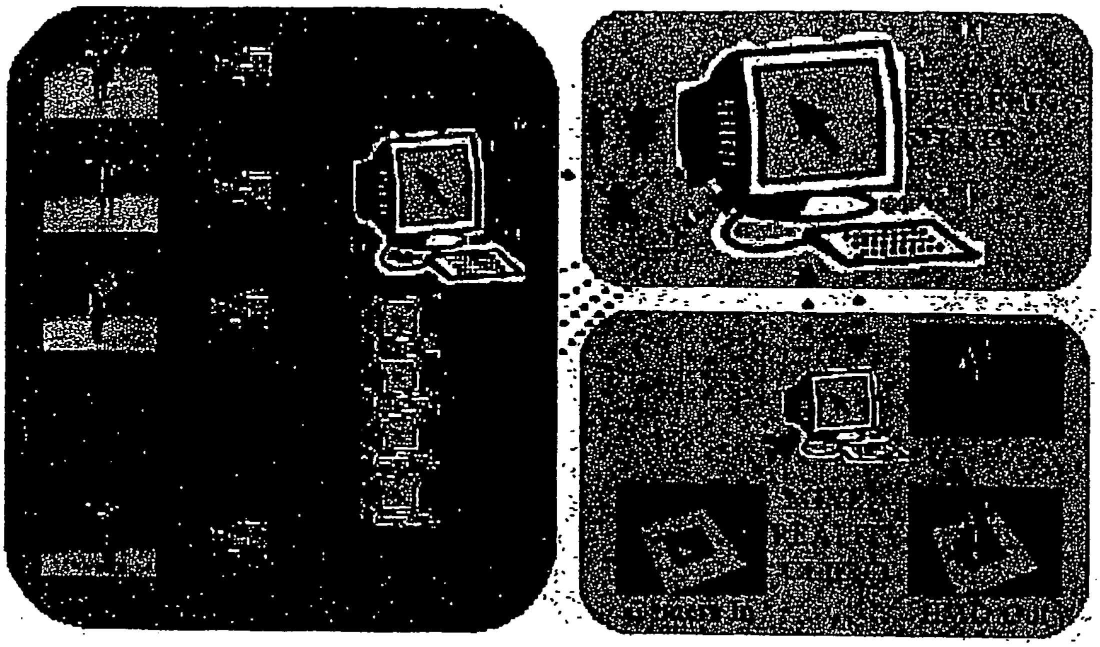


Fig. 11

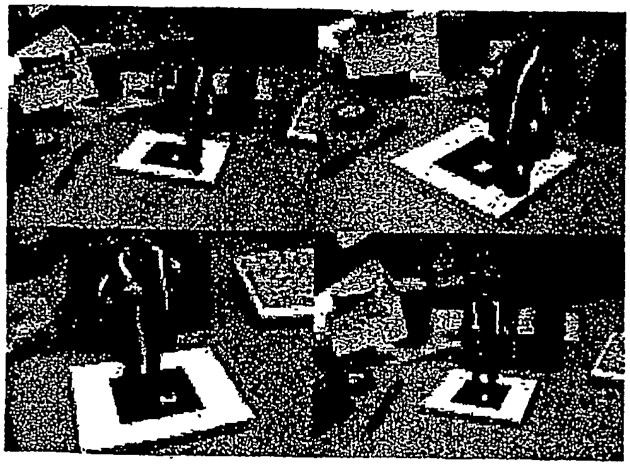


Fig. 12

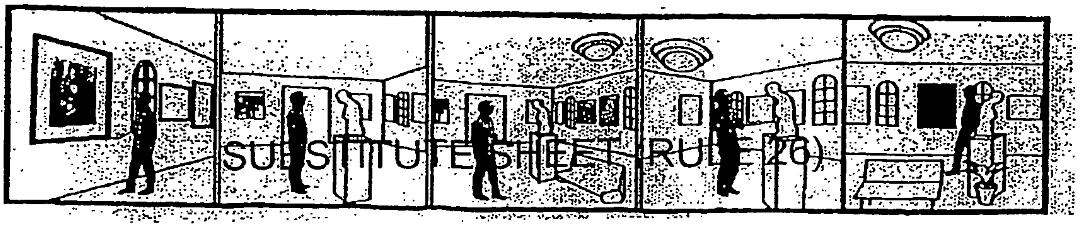
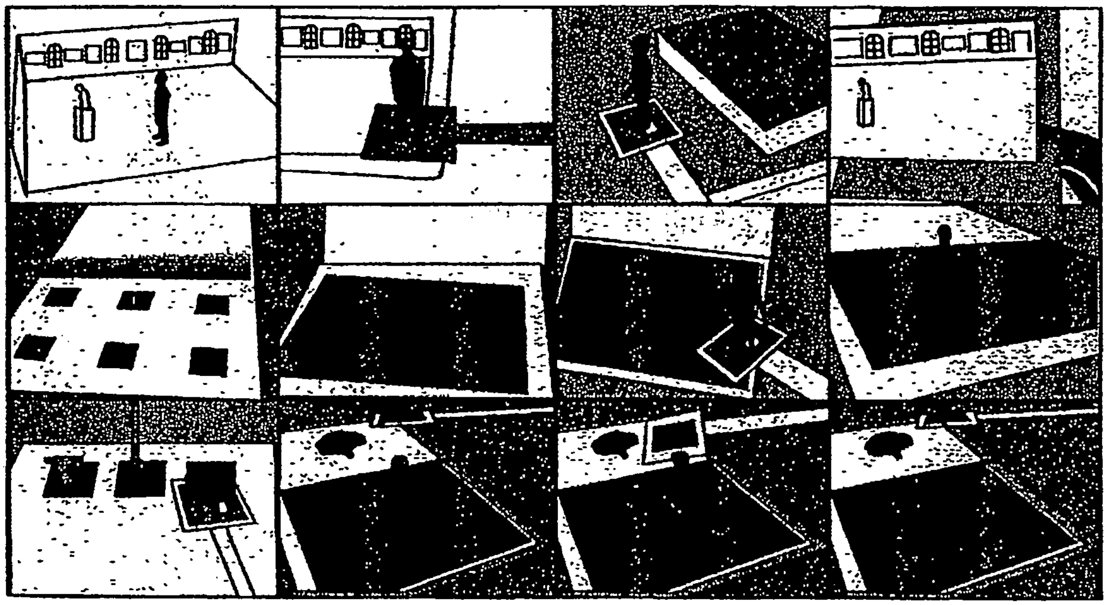


Fig. 13



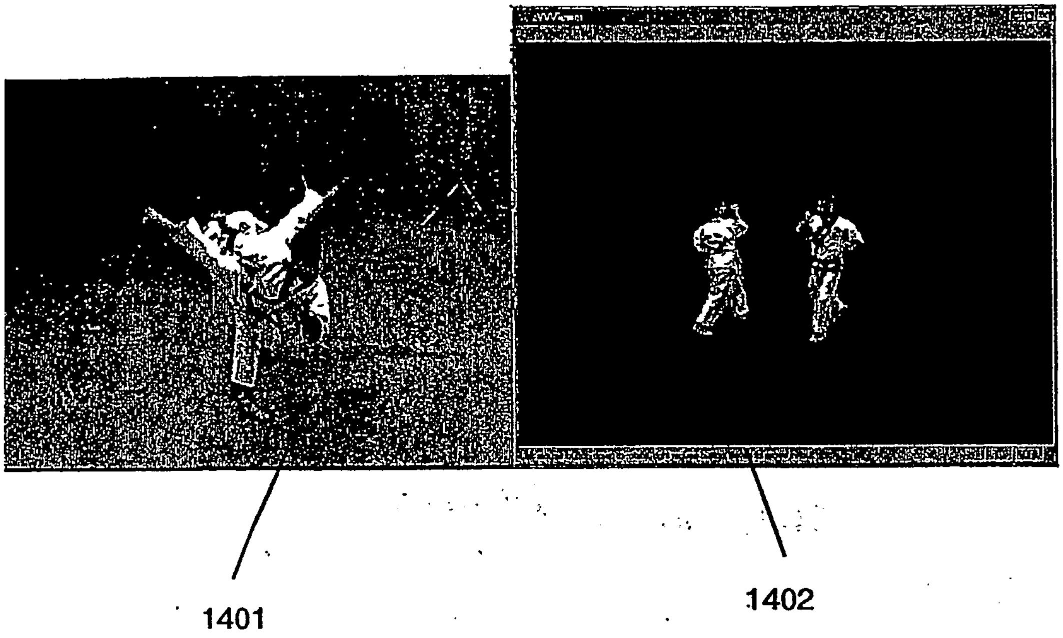


Fig. 14

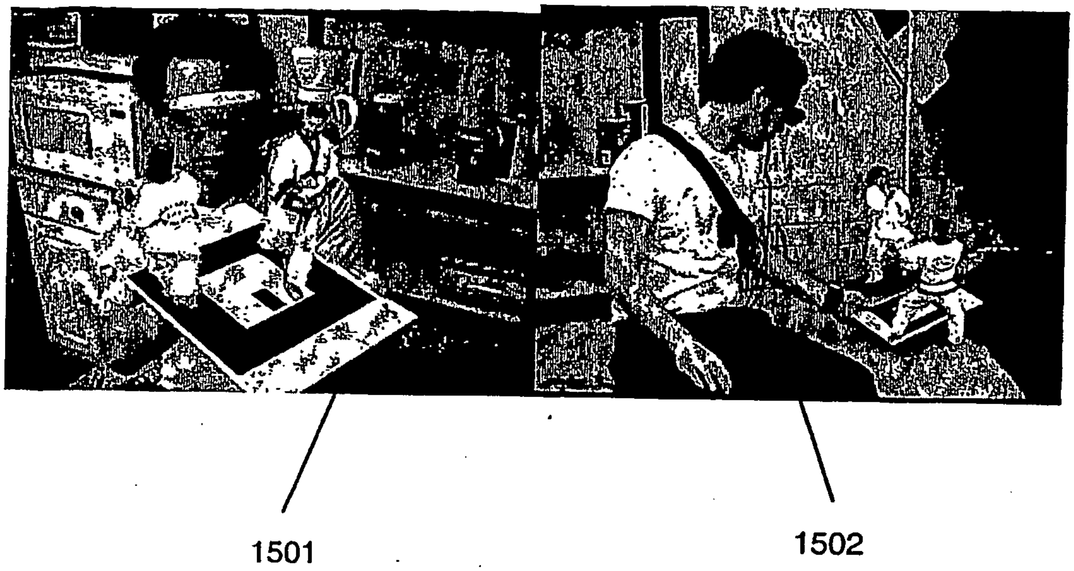


Fig. 15

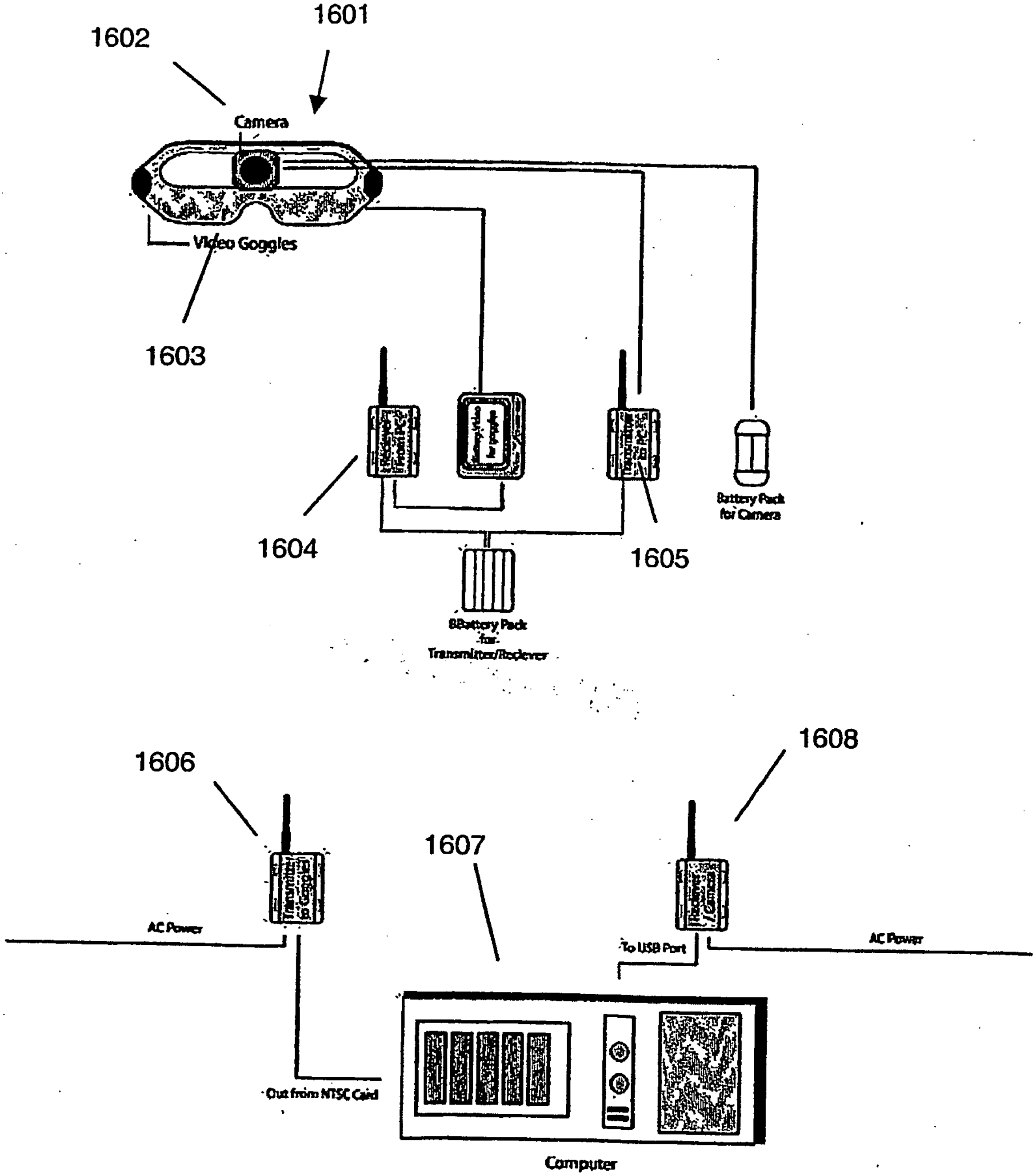

1602
1601
Camera
Video Goggles
1603
Battery Pack
for Camera
1604
1605
8Battery Pack
for
Transmitter/Reciever
1606
1608
1607
AC Power
To USB Port
AC Power
Out from NTSC Card
Computer

Fig. 16

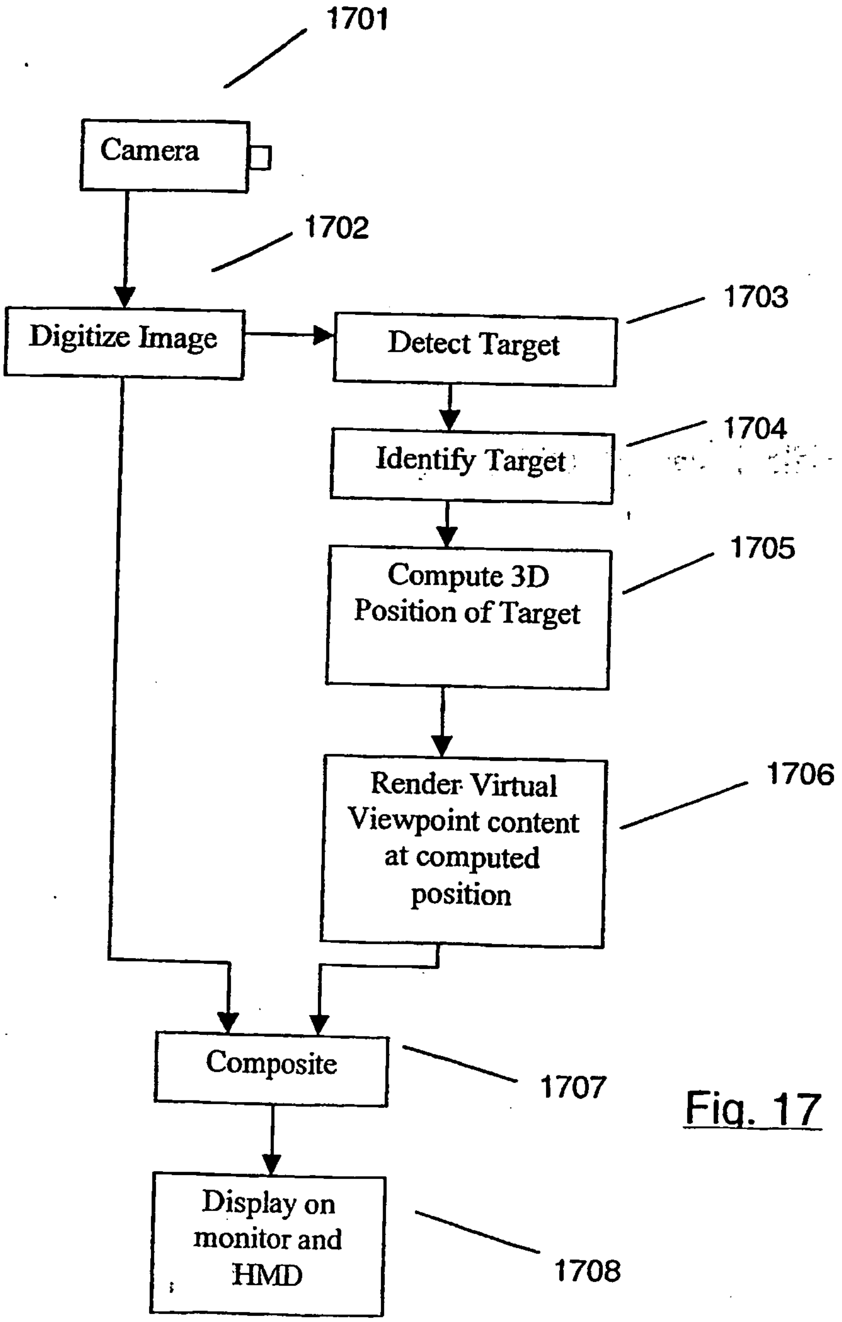
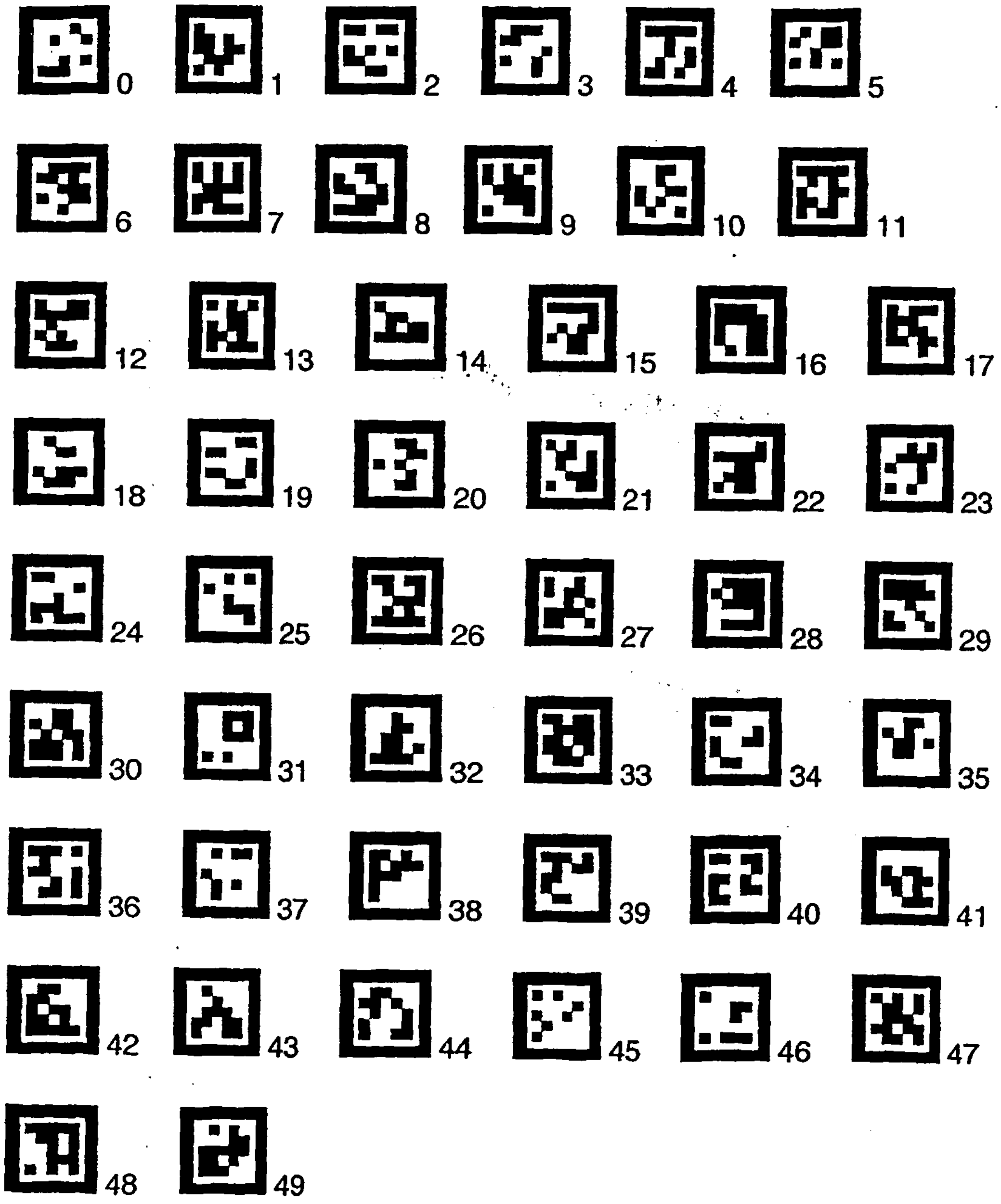

1701
Camera
1702
Digitize Image
Detect Target
1703
Identify Target
1704
Compute 3D Position of Target
1705
Render Virtual Viewpoint content at computed position
1706
Composite
1707
Display on monitor and HMD
1708

Fig. 17


0
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19
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31
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Fig. 18

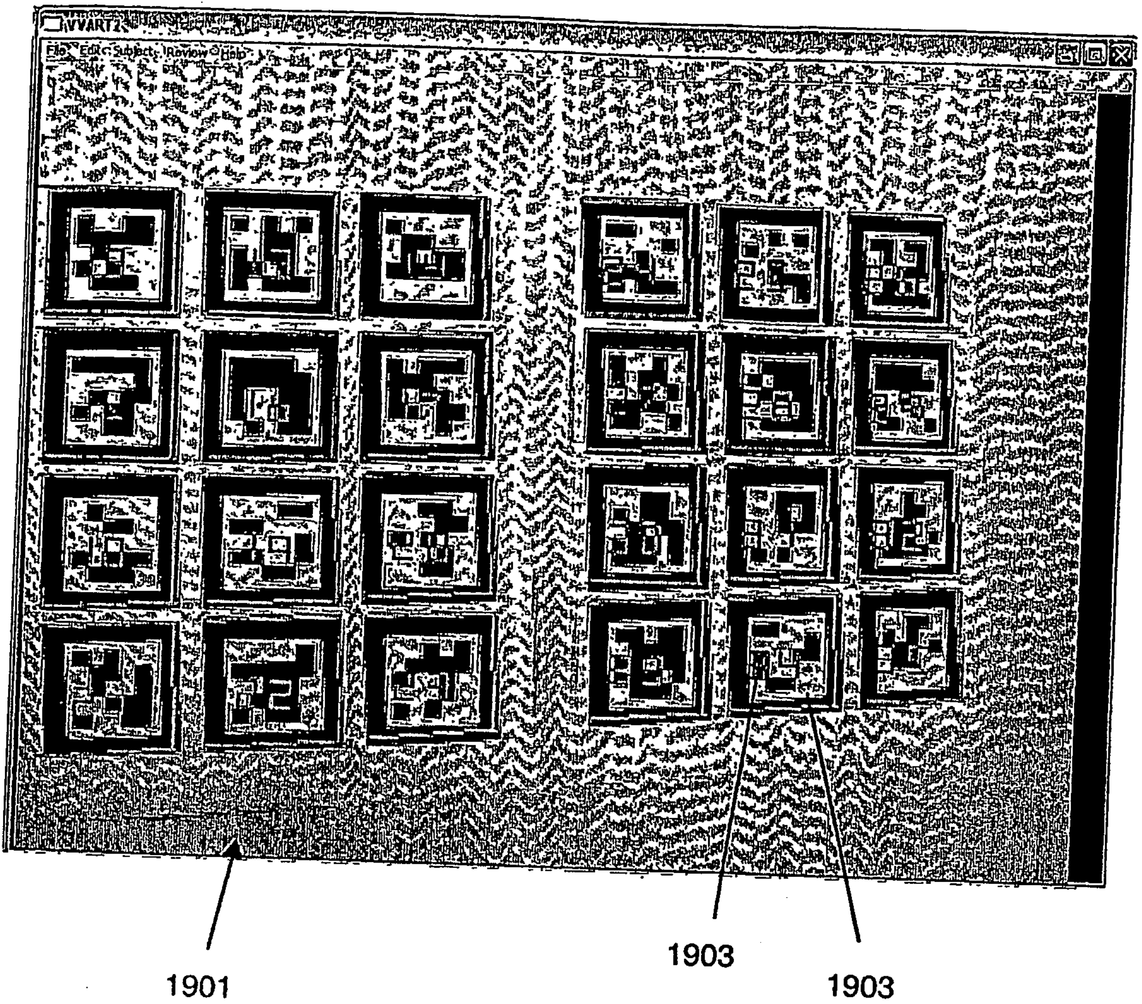

Fig. 19

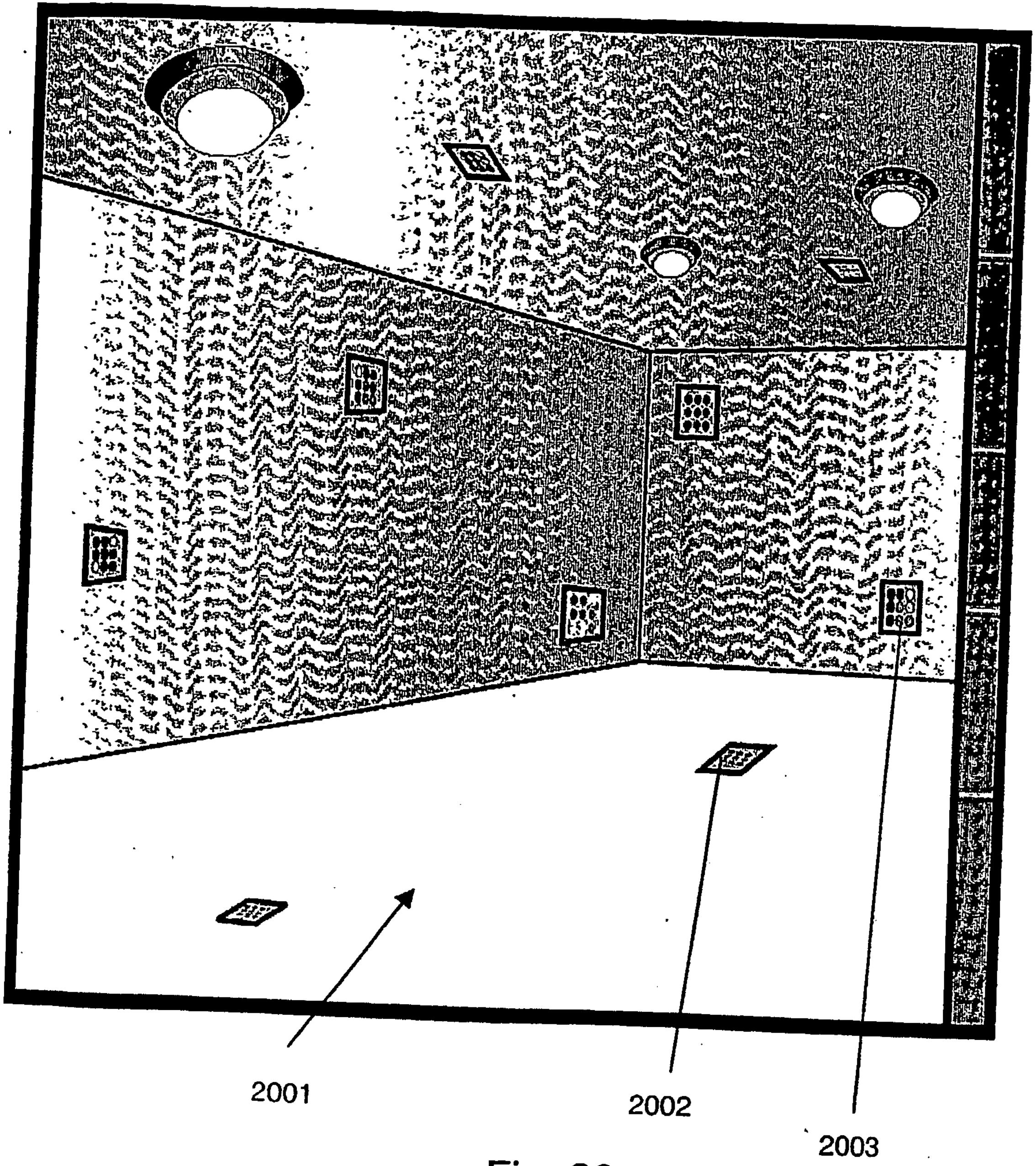

Fig. 20

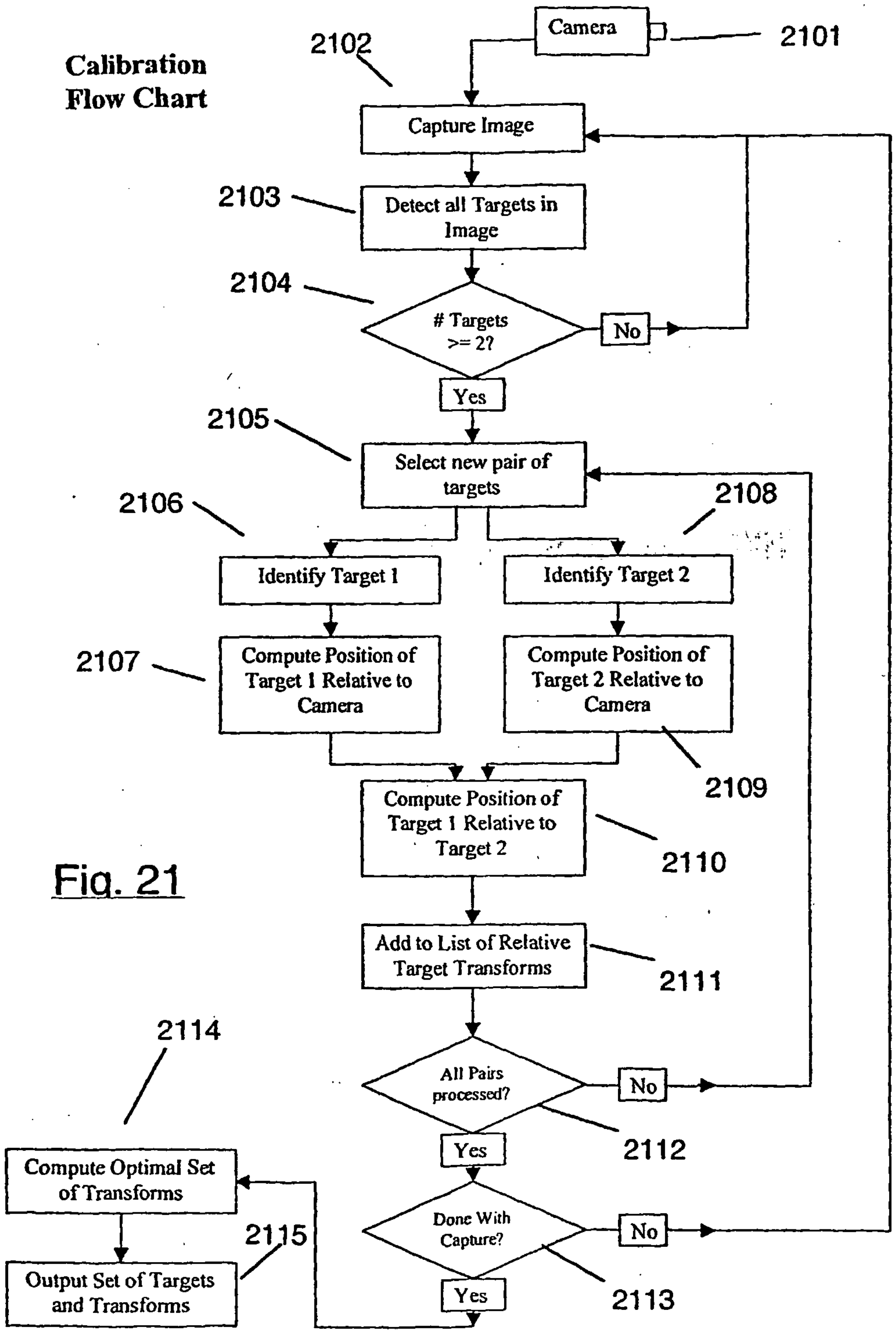
Calibration
Flow Chart
Camera
2101
2102
Capture Image
2103
Detect all Targets in Image
2104
# Targets >= 2?
No
Yes
2105
Select new pair of targets
2106
2108
Identify Target 1
Identify Target 2
2107
Compute Position of Target 1 Relative to Camera
Compute Position of Target 2 Relative to Camera
2109
Compute Position of Target 1 Relative to Target 2
2110
Add to List of Relative Target Transforms
2111
2114
All Pairs processed?
No
Yes
2112
Compute Optimal Set of Transforms
Done With Capture?
No
2115
Output Set of Targets and Transforms
Yes
2113

Fig. 21

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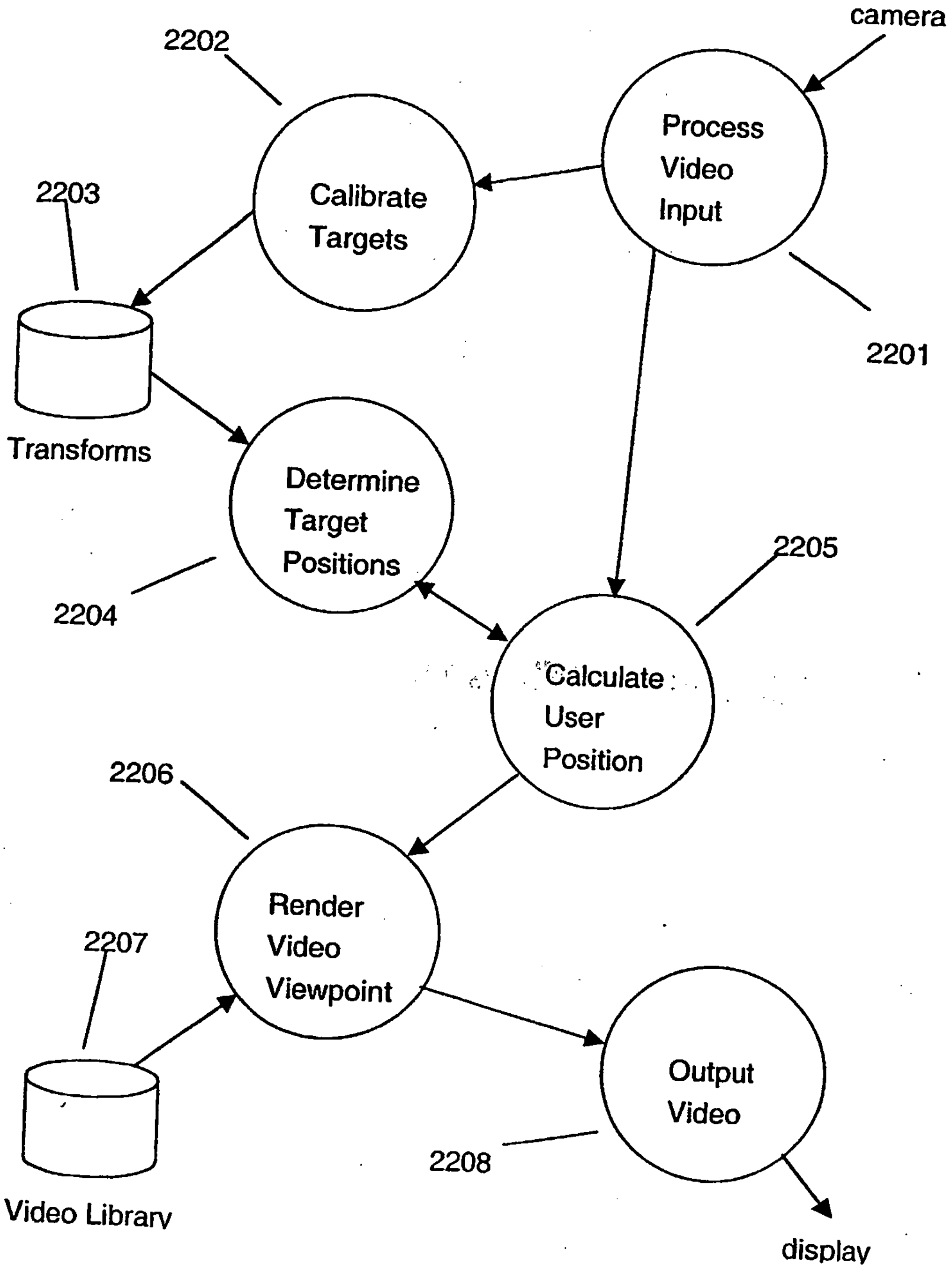
camera
Process Video Input
2201
2202
Calibrate Targets
2203
Transforms
Determine Target Positions
2204
2205
Calculate User Position
2206
Render Video Viewpoint
2207
Video Library
Output Video
2208
display

Fig. 22